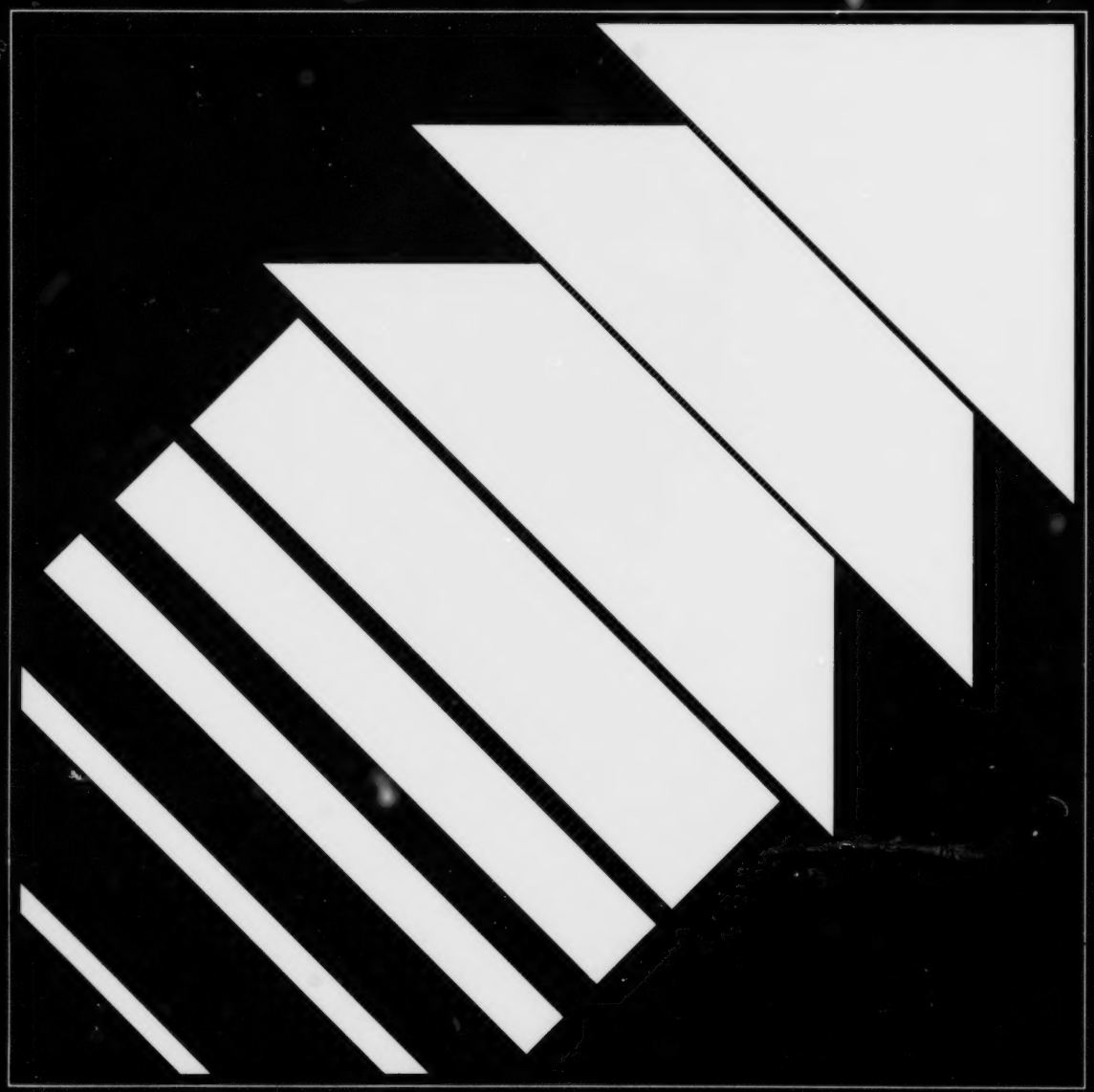
NATIONAL URANIUM TAILINGS PROGRAM



Energy, Mines and Resources Canada
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NATURALLY OCCURRING RADIONUCLIDES ON LAKE SEDIMENTS IN THE VICINITY OF AN OPERATING URANIUM MILL IN NORTHERN SASKATCHEWAN

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NATURALLY OCCURRING RADIONUCLIDES ON LAKE SEDIMENTS IN THE VICINITY OF AN OPERATING URANIUM MILL IN NORTHERN SASKATCHEWAN

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MICROMEDIA

EXECUTIVE SUMMARY

The National Uranium Tailings Program (NUTP) has as its mandate, the formation of a predictive mechanical model for the long-term fate of naturally occurring radionuclides introduced into the environment as a result of uranium mining and milling operations. This project was carried out to further understand the role of sedimentation in the removal of these radionuclides from the aquatic environment. Sediment core samples were taken from Horseshoe Pond and its vicinity in northern Saskatchewan. This lake is downstream from the Rabbit Lake tailings area and effluent treatment system of Eldor Mines Limited. The activity levels of U-238, U-234, Th-232, Th-230, Th-228, Ra-228, Ra-226 and Pb-210 were measured in the cores and reported as a function of depth. Their distribution between the organic and inorganic phases of the sediment were also determined. Based on the limited amount of data available the main findings can be summarized as follows:

- From analysis of the sediment interstitial water, it appears that the net downward movement of lake water into the sediment, rather than the net upward movement of ground water into the lake is taking place.

- The highest activity levels are found at sediment depths of between 0 and 15 centimeters and are attributed to U-238, U-234, Ra-226 and Pb-210. For the first 10 to 20 centimeters, uranium activity exceeded Th-230 activity by more than 30 times.

- More than 80% of Ra-226, Th-230 and Pb-210 in the first 5 centimeters were attached to the inorganic phase of the sediment.

- The data suggests that the majority of the Ra-226 in the inorganic phase is present as either an adsorbed ionic species, such as Ra^{++}, or as in independent and precipitated inorganic solid such as radium sulfate.

- More than 90% of the uranium is attached to the organic phase of the sediment.

- The activity of Pb-210 in the first 10 centimeters of sediment is consistent with the activity expected from Ra-226 in-growth.

- Comparison with a limited amount of historical data suggests that the first 5 to 10 centimeters of Horseshoe Pond sediment reflect the influence of the recent mining activity.

- An approximate calculation suggests that 10±5% of the uranium and 15±5% of the Ra-226 that has entered Horseshoe Pond, as a result of the nearby mining operation, has been accumulated by the pond bottom sediment.

TABLE OF CONTENTS

	PAGE
Executive Summary	-i-
Table of Contents	-iii-
List of Tables	-v-
List of Figures	-vii-
I. INTRODUCTION	
1.1 Role of Uranium Decay Series Disequilibrium in the Study of Lake Sediments	I-1
1.1.1 Uranium Isotopes	I-1
1.1.2 Thorium Isotopes	I-7
1.1.3 Radium-226	I-8
1.1.4 Lead-210 and Polonium-210	I-10
1.2 Project Background	I-10
1.3 Previous Studies	I-13
1.4 Description of Study Area	I-16
1.5 Methodology	I-16
1.5.1 Sample Collection	I-16
1.5.2 Analytical Procedures	I-19
1.5.3 Quality Control	I-21
II. HISTORICAL STUDY AREA INFORMATION	II-2
2.1 Influence of Rabbit Lake Mining on Upper Link Lake Sediments	II-6
III. RESULTS AND DISCUSSIONS	III-1
3.1 Interstitial Water Analysis	III-1
3.2 Whole Sediment Analysis	III-16

TABLE OF CONTENTS (Cont'd)

		PAGE
3.3	Separation and Analysis of the Organic and Inorganic Portions of Lake Sediments	III-29
3.4	Total Organic Matter Content of Horseshoe Pond Sediments	III-37
3.5	Estimated Impact of Mining Operation on Horseshoe Pond and its Sediments	III-41
IV.	SUMMARY	IV-1
V.	REFERENCES	V-1
VI.	APPENDIX	VI-1

LIST OF TABLES

Table		PAGE
1	Standard Reference Materials	I-23
2	Analytical Data for Lake Bottom Sediments Derived from the Environmental Survey of Wollaston Lake, Saskatchewan by W.W. Sawchyn, Saskatchewan Research Council. Samples were collected in August, 1972. (Taken directly from Garratt 1984).	II-2
3	Activity Ratios in Sediments of Rabbit Lake Drainage System as Reported by Sawchyn in 1973	II-3
4	Analytical Data for Lake Bottom Sediments Derived from the Reconnaissance Survey by E.M. Cameron and S.B. Ballantyne, Geological Survey of Canada. Samples collected September, 1974. (Taken directly from Garratt 1984).	II-5
5	Radiochemical Data on Lake Sediments Taken Downstream from the Beaverlodge, Saskatchewan Mining and Milling Operation. (Taken from Garratt 1984)	II-7
6	Activity Ratios in Sediments Taken Near Beaverlodge Mining Operation by Garratt (1974)	II-8
7	Radionuclide Levels in Sediment Cores from Rabbit Lake Area, 1980 (Taken from Saskmont 1980)	II-9
8	Activity Ratios (Calculated from Table 7)	II-14
9	Radionuclide Levels in Sediment Cores from Upper Link Lake as per Saskmont Ltd., Interim Report on the Investigation of Radionuclide Levels in the Rabbit Lake Drainage System, March, 1982 (Saskmont 1982) (Taken from Garratt 1984)	II-22
10	Detailed Radiochemical Analysis of Upper Link Lake Sediment Core 28A (Taken from Saskmont 1980)	II-30
11	Water Quality Analysis for Horseshoe Pond	III-2
12	Data from the Analysis of Interstitial Water Removed from Sediment Cores Taken at Horseshoe Pond	III-3
13	Radiochemical Data from the Analysis of Interstitial Water Removed from Sediment Cores Taken at Horseshoe Pond	III-4

LIST OF TABLES (Cont'd)

Table		PAGE
14	Radiochemical Analysis of Sediment Cores Taken from Horseshoe Pond (All data reported on dry sediment basis)	III-22
15	Radiochemical Contents of Sediment Core Taken from Hidden Bay (All data is reported on basis of dry whole sediment)	III-30
16	Radiochemical Contents of the Organic Portion of Sediment Cores Taken from Horseshoe Pond (All data is reported on basis of content in dry whole sediment)	III-31
17	Radiochemical Contents of the Inorganic Portion of Sediment Cores Taken from Horseshoe Pond (All data reported on basis of dry whole sediment)	III-32
18	Radiochemical Contents of the Organic Portion of Sediment Cores Taken from Hidden Bay (All data reported on basis of dry whole sediment)	III-33
19	Radiochemical Contents of the Inorganic Portion of Sediment Cores Taken from Hidden Bay (All data reported on basis of dry whole sediment)	III-34
20	Comparison of Methods for the Determination of Organic Contents of Lake Sediments	III-40
21	Activity Level per Gram Organic Carbon and Activity Ratios in Organic Portion of Horseshoe Pond Sediment (Calculated from Table 16)	III-42
22	Activity Level per Gram Organic Carbon and Activity Ratios in Organic Portion of Hidden Bay Lake Sediment (Calculated from Table 18)	III-43
23	Uranium Activity Levels per Gram of Sediment Organic Carbon. Data is Historical Data Normalized to Hydrogen Peroxide Procedure	III-44

LIST OF FIGURES

Figure		PAGE
1	Distribution of U-234/U-238 Values in Water from I, Economic Uranium Deposits and II, Non-Economic ("disseminated") Uranium Occurrences (Taken from Cherdyntsev (1971) based on work by Syromyatnikov)	I-4
2	General Schematic of Study Area	I-17
3	Schematic of Study Area. Horseshoe Pond Relative to Parks Lake and Hidden Bay	I-18
4	Radionuclide Contents of Lake Sediment Plotted as a Function of Sediment Depth, 1980 data (taken from Saskmont 1980)	II-10
5	Radionuclide Contents of Lake Sediment Plotted in Terms of Activity Ratio as a Function of Depth, 1980 data	II-15
6	1981 Radionuclide Content of Upper Link Lake Sediment Cores Plotted as a Function of Sediment Depth (Taken from Saskmont 1981)	II-24
7	Plot of U-238/Ra-226 Activity Ratio as a Function of Depth in Upper Link Lake Sediments, 1981 (Taken from Saskmont 1981)	II-27
8	Plot of U-238/Th-230 and Th-230/Ra-226 Activity in Upper Link Lake Sediment Core 28A as a Function of Depth	II-31
9	Plot of Water Content of Horseshoe Pond Sediment Cores as a Function of Depth	III-6
10	Plot of Ion Concentrations in Interstitial Waters of Horseshoe Pond Sediment Cores as a Function of Depth; A-Sulfate; B-Chloride; C-Calcium; D-Manganese; E-Magnesium; F-Sodium; G-Uranium	III-8
11	Total Cationic Concentrations in the Interstitial Waters of Horseshoe Pond Sediment Plotted as a Function of Depth	III-14
12	pH of Interstitial Waters of Horseshoe Pond Sediment as a Function of Depth	III-15
13	Uranium and Radium-226 Profile in Horseshoe Pond Sediments as a Function of Depth; A-Core HL-1; B-Core HL-2; C-Core HL-3; D-Core HL-4	III-17

LIST OF FIGURES (Cont'd)

Figure		PAGE
14	Plot of Ra-226/Th-230 in Horseshoe Pond Sediments as a Function of Depth	III-24
15	Plot of U-234/U-238 in Horseshoe Pond Sediments as a Function of Depth	III-27
16	Plot of U-238/Th-230 in Horseshoe Pond Sediments as a Function of Depth	III-28
17	Distribution of Ra-226 in Sediment Cores Between the Organic and Inorganic Phases	III-36
18	Plot of U-234/U-238 Ratio in the Whole Sediment of Horseshoe Pond as a Function of Depth	III-38
19	Plot of U-234/U-238 Ratio in the Organic Portion of Horseshoe Pond Sediment as a Function of Depth	III-39

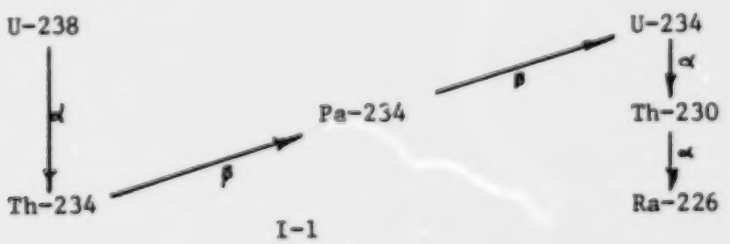
I. INTRODUCTION

1.1 Role of Uranium Decay Series Disequilibrium in the Study of Lake Sediments

The study of radionuclides in the uranium-238 (U-238) series can often provide valuable information on the age of mineralization, the state of equilibrium, and the migration of uranium in near surface deposits (Levinson and Coetzee 1978). While possibly dealing with a shorter term system, the study of this disequilibrium should, nevertheless, also provide valuable information on the past and recent history of lake sediments. Hopefully it can be used to differentiate between the influence of man on the environment and the influences of nature itself.

1.1.1 Uranium Isotopes

There are three naturally occurring isotopes of uranium, U-238, U-235 and U-234. U-235 (half life ($t_{\frac{1}{2}}$) = 7.1 x 10^9 years) and U-238 ($t_{\frac{1}{2}}$ = 5.1 x 10^9 years) are long-lived isotopes whose abundance in the earth have been decreasing logarithmically through geologic time. Both are easily detected and can be measured accurately in rocks and in natural waters. Their relative activity ratio in nature is usually constant at 0.046 (Rogers et al. 1969, Hamer et al. 1960). U-234, the third naturally occurring uranium isotope, has a half life of 2.5 x 10^5 years. This isotope is generated in nature from its parent, U-238, by way of intermediate, short-lived nuclides, Th-234 ($t_{\frac{1}{2}}$ = 24 days) and Pa-234 ($t_{\frac{1}{2}}$ = 1.2 minutes). Therefore, its worldwide abundance is determined by the abundance of U-238.



The radioactivity of an unstable isotope is given by:

$$A = \lambda N \tag{1}$$

where A is its activity in disintegrations per unit time, N is the number of atoms in the system, and λ is the decay constant, the fraction of atoms decaying per unit time. If secular equilibrium has been achieved between a radioactive parent and a radioactive daughter, the activities of the two are equal:

$$A_p = A_d \tag{2}$$

where subscript p denotes parent and d denotes daughter.

Therefore:

$$N_p \lambda_p = N_d \lambda_d \tag{3}$$

For U-234 and U-238, Np/Nd is equal to 0.000055. A common measurement technique is to measure the relative activity abundances of the two isotopes by alpha spectrometry. This measurement, usually referred to as the U-234/U-238 ratio, is exactly 1.00 for natural unweathered uranium. Even in open systems, such as weathered minerals and in natural waters, significant deviations from 1.00 are not expected because of the small mass differences and because of the very short half-lives of the two intervening daughters in the decay chain, Th-234 ($t_{\frac{1}{2}}$ = 24 days) and Pa-234 ($t_{\frac{1}{2}}$ = 1.2 minutes). Thus, interest in the ratio was generated 30 years ago by the discovery that large deviations do occur in nature, particularly in ground and surface water (Cherdyntsev et al. 1955). From this finding, opportunities for the use of U-234/U-238 activity ratio in hydrogeological studies, age dating and marine chemistry have developed. Much of what is known about U-234 has been summarized in a book by Cherdyntsev (1971). Osmond and Cowart (1976) have updated

Cherdyntsev's work with particular emphasis in hydrologic systems. One of the most important theories concerning U-234 is that it is more likely to be in the higher oxidation state (6+) than is U-238. As a result, it is likely to be more mobile in natural waters than is U-238. Several mechanisms have been suggested to support this theory. Cherdyntsev and co-workers based their mechanism on "alpha particle recoil" (Cherdyntsev 1971) while Rosholt et al. (Dooley 1966) suggested a variation on this mechanism. Kolodny and Kaplan (1970) suggested a third mechanism for increasing the oxidation state of uranium from 4+ to 6+ during the radioactive transformation of U-238 to U-234. Their mechanism proposes an increase in the positive charge of the ions caused by the beta decays of Th-234 and Pa-234.

Variation in the U-234/U-238 activity ratio from secular equilibrium (ratio = 1.0) is common (Rosholt 1963, 1965, 1965) in sedimentary environments. Charlov (1959) has noted the tendency of residual materials to be deficient in U-234 and redeposited materials to contain excess U-234. The earth's oceans have an activity ratio of about 1.15. It has been reported (Isabaev et al. 1960) that mountain streams also have U-234/U-238 activity ratios greater than unity.

Very early studies by Cherdyntsev in 1955 had shown that waters from rocks enriched in uranium often contain excess U-234, whereas "extracts" (i.e. various leachates) from uranium minerals typically contain U-234 and U-238 in equilibrium amounts. The application of this concept is illustrated in Figure 1 in which the striking difference between the U-234/U-238 activity ratio of waters from uranium ore deposits are compared with waters from non-economic uranium occurrences. The former yield ratios of approximately 1.0 whereas the latter generally have a distribution of between 2.5 and 6.5, and may have large isotope shifts as high as 12. Cherdyntsev (1971, p. 82) explained this on the basis of the location of the

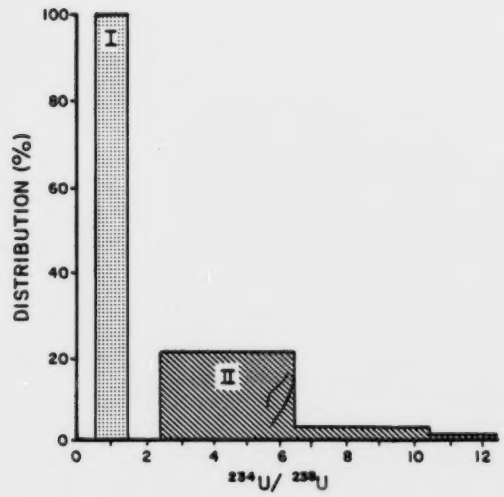


FIGURE I

DISTRIBUTION OF U-234/U-238 VALUES IN WATER FROM
I ECONOMIC URANIUM DEPOSITS AND
II NON-ECONOMIC ('DISSEMINATED') URANIUM OCCURANCES

(Taken from Cherdyntsev (1971) based on work by Syromyatnikow)

uranium atoms in crystal lattices. Specifically, in uranium minerals of economic deposits, the U-234 recoil atoms are able to occupy the positions of U-238 atoms and when the element is leached, both isotopes pass into solution to about the same extent (activity ratio = 1). When the uranium atom is an accessory or minor constituent in a mineral (e.g. apatite, monazite) or rock, and is uneconomic as an ore deposit, the U-234 recoil atom leaves its original position and is not able to find a suitable crystallographic site. It then migrates to microfractures where it is more susceptible to leaching and a high activity ratio results in the waters.

Uranium Mobility with Aqueous Environment

In oxidizing aqueous environments, in general, uranium iself is more mobile than any of its daughters. Because of this inherent mobility, disequilibrium will exist between U-238 and its daughters. This disequilibrium may be used to help elucidate recent and past sediment history. The mobility of uranium in the secondary environment is governed primarily by three factors (Levinson 1980):

(1) its variable oxidation state. As discussed above, uranium can exist in a hexavalent (uranic; U^{6+}) state which, when it forms complexes, is much more soluble than tetravalent uranium. For all practical purposes, U^{4+} can be considered to be insoluble. The high solubility of uranium in the surface environment is due to the oxidation of uranium to U^{6+} in aerated or near-surface oxidizing environments.

(2) its tendency to form complexes with a large number of naturally occurring anions. Uranium forms complexes with many components in natural aqueous systems. Langmuir (1978) has reported a total of 43: fifteen with water; ten with fluoride; nine with phosphate; four with sulfate;

three with carbonate; and two with chloride. The importance of each will depend on the pH, Eh and on the activities of the various anions. The most important complexes are those of the carbonates (uranyl dicarbonate and uranyl tricarbonate) and several phosphates, particularly the uranyl acid biphosphate, $UO_2(HPO_4)_2^{=}$. The importance of phosphate complexes has only recently been recognized and, in fact, they are probably more stable than the carbonate complexes under certain conditions (Langmuir 1978). In the presence of phosphate, even as little as 0.1 ppm at low temperatures, phosphate complexes dominate the slightly acid to slightly alkaline pH range. Therefore, uranium is generally transported as some uranyl complex, and deposition takes place upon reduction to the U^{4+} state.

(3) its tendency to be adsorbed on organic matter and mineral surfaces. Adsorption of uranium is not efficiently executed by organic matter of various types, such as is found in bogs and organic-rich lake sediments. Following adsorption, the uranyl ion may be reduced to U^{4+}. Various other materials, such as zeolites, clays and iron oxide and hydroxides, may also be adsorbers of uranium to varying degrees and under certain environmental conditions.

Uranium Deposition onto Lake Sediments

There are several mechanisms by which uranium is deposited onto lake sediments, from the aqueous environment. In most cases, the uranium will be out of secular equilibrium because enough time will not have elapsed to allow the U-234 to decay into equilibrium with U-238.

- The reduction of $U6^{+}$ to U^{4+} will result in the formation of uraninite or other uranous forms. This mechanism explains the occurrence of uranium in roll front deposits (Harshman 1972), bogs, coal beds and organic lake sediments. Methane has been postulated as the reductant in the formation of Rabbit Lake and other large deposits in Saskatchewan (Hoeve and Sibbald 1978). Other mobile reductants of importance include hydrogen sulfide, other hydrocarbons and hydrogen.

- Adsorption of uranyl complexes by organic matter and other materials, e.g. clays and iron oxides, certainly reduce the mobility of uranium. Evidence (Levinson 1974) appears to be emerging that following the initial adsorption of the uranyl complexes, there may be subsequent reduction and precipitation by mobile reductants, such as methane and hydrogen sulfide.

- Uranyl ion (in an oxidizing environment) can be precipitated from solution when it combines with vanadate, phosphate, arsenate, silicate, carbonate or sulfate anions in association with Ca, Mg, K, Ba, Pb, Cu and several other elements (Levinson 1974).

1.1.2 Thorium Isotopes

Cherdyntsev (1971, pp. 111-113) showed how the activity ratio Th-230/Th-232 can be used in the interpretation or corroboration of other isotopic data (particularly the activity ratios U-234/U-238 and Ra-228/Ra-226) collected in connection with uranium exploration. The Th-230/Th-232 activity ratio in rocks of the earth's crust is approximately 0.8, and it is somewhat higher in natural waters owing to the greater tendency of rocks to release Th-230 to natural solutions (Ivanovich and Harmon 1982, pp. 367).

In the vicinity of economic uranium deposits, however, this ratio may become from ten to hundreds of times greater, as thorium (Th-232) is not normally associated with uranium deposits. Th-230 is more often determined when information on the age of mineralization, the state of equilibrium, and the extent and timing of uranium migration in near surface environments is needed. In such cases, the activity ratios of Th-230/Th-234, Th-230/Pa-231 and Ra-226/Th-230 are likely to be obtained. Lively et al. (1979) used the Th-230/U-234 and Ra-226/Th-230 activity ratios to study the extent of leaching and re-deposition at the Yeelirrie deposit in western Australia.

In general, it can be said that fractionation of Th-230 from its parent (U-234) and daughter (Ra-226) nuclides takes place in most environments because thorium is insoluble in aqueous media relative to uranium (averages for river water: Th = 0.1 ppb and U = 0.4 ppb) (Langmuir and Herman 1980). Therefore, uranium and radium move away resulting in disequilibrium between Th-230, Ra-226 and U-234 (Paul and Pillai 1986, Paul et al. 1980).

1.1.3 Radium-226

Except for uranium and radon-222 (Rn-222), Ra-226 is the most important nuclide in the U-238 decay chain as far as surface mobility and deposition is concerned. Ra-226 may be mobile in some surficial environments, specifically in the reducing environment, in which uranium itself is immobile. As a result, Ra-226 ($t_{\frac{1}{2}}$ = 1600 years) is a potential pathfinder for uranium, even though it is usually out of equilibrium with its parents in aqueous surficial environments. Radium is an alkaline-earth element and its chemical behaviour is similar to that of barium. As such, some compounds of radium, such as the sulfates, have very low solubilities. Radium also forms soluble species with the chloride ion as evidenced by the high radium content of deep, chloride-type brines (Tanner 1964).

However, even though radium can be leached from its parent Th-230, there are several natural mechanisms by which its mobility can be reduced or stopped, at least temporarily, in the waters of the surficial environment: co-crystallization, co-precipitation, inorganic adsorption and biological absorption into living organisms. Co-crystallization occurs when radium is able to substitute for barium in barite, resulting in the so-called "radiobarite". Since neither uranium nor thorium can occupy such structural positions, the "unsupported" radium will have more than 99% disappeared within ten half-lives, or about 16,000 years. Since it contains "unsupported" Ra-226, the presence of radiobarite indicates that geological processes, such as active leaching of pyrite-containing uranium ores has probably taken place within the past 20,000 years. The suggested scenario is that sulfuric acid was formed, uranium was leached away as a soluble uranyl sulfate complex and radium was coprecipitated with barium as radiobarite. It has been reported (Heinrich 1958) that it is this mechanism that led to the source of radioactivity that originally attracted attention to the Blind River, Ontario, uranitite deposit. Co-precipitation of radium may occur where Fe-Mn oxides and hydroxides are being precipitated, such as at the orifices of springs. While, in actual practice, it is difficult to determine whether radium is co-precipitated or adsorbed by Fe-Mn oxides there is convincing evidence (Jenny 1968) to indicate that it is the Fe-Mn oxides rather than the clay minerals in soils and sediments, which are the controlling factors in the fixation of heavy metals such as Zn, Cu, Ni and Co. Adsorption of radium may be affected by Fe-Mn oxides, clay minerals or humus (Buckman and Brady 1969). Clay minerals preferentially adsorb alkaline-earth cations (including radium) in preference to univalent cations. Biological absorption of radium by vegetation exists because plants have minimum physiological barriers to radium (Kovalavskiy 1975, Whitehead et al. 1971). As far as plants are concerned, radium is similar to Ca or Ba. Since almost all plants die within the 1600 year half-life of Ra-226, and Ra-226

is released during subsequent decay, biological absorption can be considered as only a temporary hindrance to the mobility of Ra-226. Autoradiographs showing that plants absorb radium have been presented by Penna-Franca and Gomes de Freitas (1963) and Penna-Franca et al. (1972).

1.1.4 Lead-210 and Polonium-210

The measurement of Pb-210 is a means of measuring Rn-222 that has decayed in a sample, since the former is a descendent of the latter. Pb-210 (half-life about 22 years) will be deposited at the site of radon decay, such as in a soil or lake sediment. After about one hundred years, Pb-210 serves as a naturally occurring integrator of the radon flux. Polonium-210 (Po-210, half-life of 138 days) follows Pb-210 in the decay sequence, being separated from it only by Bi-210 (5 day half-life). Either Bi-210 or Po-210 could serve as a measure of the Pb-210 abundance, but the determination of Po-210 by alpha spectrometry is significantly easier than the determination of either Bi-210 or Pb-210, both of which are beta emitters. If secular equilibrium between the two isotopes can be assured, Po-210 is an indirect way of measuring Pb-210 in soil and lake sediment. Allowing a sample to sit for more than 700 days, prior to analysis, will ensure greater than 99% equilibrium between the two.

1.2 Project Background

The National Uranium Tailings Program (NUTP) has as its mandate, the formation of a predictive mathematical model for the long-term fate of naturally occurring radionuclides introduced into the environment as a result of uranium mining and milling operations. These radionuclides can be removed from the environment by several mechanisms, including adsorption or precipitation onto lake or river sediments. To understand the role of

sedimentation in the removal of radionuclides from the aquatic environment, a literature review of the subject was carried out and a report prepared (Monenco 1985). In summary, that report highlighted the following:

1. The radionuclides which are of major interest, relative to the impact of uranium mining and milling on the aquatic environment, are Ra-226, Ra-228, Pb-210, U-238, U-234, Th-230 and Th-232.

2. There has been no definitive study of the speciation of the dissolved radionuclides in the aquatic environment. Variables such as solution pH and redox potential, will influence the form of the cations. The most likely organic material to be involved with the complexation of radionuclides is humic acid, since it is known to form complexes with a variety of metals (Kerekes 1973, 1975; Oliver et al. 1983; Kerekes, 1977).

3. Biological organisms can remove radionuclides from surface water by: (i) adsorption to their exoskeleton or cell wall, (ii) self absorption, and/or (iii) consumption of contaminated detritus. In all three mechanisms, the death of these organisms will transfer the radionuclides to the sediment. It is not known how much biological organisms contribute to the removal of radionuclides from surface water. There is very little information on the subject in the literature.

4. There is virtually nothing known about the sedimentation history of lakes known to be affected by uranium milling operations. Whether sediment cores collected from these areas can be used to define a sedimentary history useful for predictive modelling can only be determined by field studies at these sites.

5. No information was found in the literature regarding remobilization of radionuclides from sediment. It has been hypothesized, however,

that remobilization can occur under anaerobic or partially anaerobic conditions.

This study was carried out in an attempt to elucidate the role that factors such as particle size, organic matter content, interstitial water composition, etc., have on the radionuclide composition of lake sediments. Evidence of remobilization of the radionuclides was to be looked for. Two lakes, located near the Rabbit Lake mining and milling activity of Eldor Mines, were identified as possible study sites. One, Upper Link Lake, has undergone unusual and rapid sedimentation processes over the past fifteen year history of the mining operation. Prior to the mine start-up, the original Rabbit Lake was dewatered into Upper Link Lake. In the course of that procedure, a large amount of the Rabbit Lake sediment was also included in the transfer (Garratt 1984). This was followed, a year or so later, by increases in the radionuclide content of the surface water runoff to Upper Link Lake, caused by the action of nature on two waste rock piles and the ore stockpile. The second water body, Horseshoe Pond (this body of water is also named Horseshoe Lake but is sometimes known as Horseshoe Pond. For the duration of this report it will be referred to as Horseshoe Pond. Its geographical coordinates are 58 degrees 3.5 minutes north latitude and 103 degrees 44 minutes west longitude), has not been subjected to such exaggerated conditions over the same time period. It has been relatively undisturbed from its natural condition. The only change that has taken place, since the mining operation start-up, is the introduction of mine tailings precipitation pond runoff. Because of its relatively undisturbed condition, Horseshoe Pond was chosen as the site for this study.

The approach of this study was, firstly, to review and assess all available data pertaining to sediments of the region and secondly, to analyze the sediment cores taken from Horseshoe Pond to determine their radionuclide contents as a function of depth. Activity ratios such as U-234/U-238, Th-228/Ra-228, Th-232/Th-228, Th-230/Ra-226 and Pb-210/Ra-226 were measured in an attempt to obtain information regarding possible mechanisms for their presence. For example, as discussed in Section 1.1, adsorption or desorption

phenomena and the source of uranium may be suggested from a knowledge of the U-234/U-238 activity ratio. By combining this type of information with organic matter content and knowledge of the distribution of the radionuclides between the organic and inorganic sediment phases, it may be possible to formulate the basis for a mechanism. The sediment pore water was also analyzed and used to help elucidate the mechanisms.

1.3 Previous Studies

The daughters of the U-238 and the Th-232 radioactive decay series can enter surface and ground water by a number of routes which include leaching of uranium ores by ground water and rain water, discharge of mining/milling waste streams containing these radioactive species in either dissolved and/or suspended forms, seepage from tailings ponds and leaching of radioactivity from waste solids. Radionuclides such as U-238, U-234, Th-230, Ra-226 and Pb-210 can enter ground and surface water where they can undergo various transformations, can be fixed in the aquifier, or be deposited in bottom sediments. As discussed in Section 1.1, many variations of radionuclide disequilibrium can result in the sediments, depending on the degree of leaching, adsorption, co-crystallization, co-precipitation and the oxidizing-reducing nature of the environment. The effect of the oxidizing-reducing conditions can be illustrated by the fact that in an oxidizing environment, as in well mixed streams and lakes, uranium is more likely to be in the 6+ state and is more mobile than radium (Hesslein and Slavicek 1984). In a reducing environment, uranium is less mobile than radium because the former is reduced to the insoluble 4+ state. A complication to this rule is the adsorption of uranium into organic matter and the effect of co-precipitation of either radium or uranium when iron and manganese oxides precipitate in oxidizing environments. In addition, environmental redox conditions can change with time. Such fluctuation may result in movement of deposited radionuclide. For example, many lakes in northern Canada are stratified during much of the year and there is no intermingling of the water masses in the upper (epilimnion) and lower (hypolimnion) parts of the lake, which may be oxidizing and reducing, respec-

tively (Turekian and Cochran 1978, Hesslein and Slavicek 1984). When the hypolimnion is reducing, uranium will likely be deposited on the bottom, whereas radium may be distributed uniformly in the water column. During subsequent mixing of the lake, the bottom may become oxidizing. As a result, uranium will then become mobile (6+ state) but radium may be precipitated (scavenged) with iron and manganese oxides, resulting in it being concentrated in the sediment.

While much laboratory data is available concerning the speciation of uranium in contaminated and uncontamined surface waters (Ivanovich and Harmon 1982), there is much less experimental information available concerning radium. Knowledge of its speciation would provide a necessary basis for better understanding the migration process. As an example, many workers have assumed that radium is dissolved in such waters only as the hydrated cation Ra^{+2}. This species might not be expected in the presence of sulfate where the formation of radium sulfate (Benes et al. 1982) would be possible. Simple calculations suggest that the relative abundance of the ion pair can be significant (> 5%) in waters containing more than 43 mg/L free sulfate ($SO_4^{=}$). Using radiotracer techniques in combination with electrophoresis, Benes and Odrzalek (1980) measured the dissolved forms of Ra-226 in river water contaminated with uranium mine effluents. The results indicated the presence of some neutral species form in amounts exceeding maximum possible abundances of radium sulfate. They speculated that these may be attributed to organic complexes.

Benes et al. (1980) have also determined particulate forms of radium using the method of selective dissolution (Benes et al. 1981). Four different forms of particulate radium were distinguished: (1) loosely bound, (2) acid soluble, (3) radium coprecipitated with barium sulfate, and (4) radium "in crystalline detritus". The main forms found were "acid soluble" and "in crystalline detritus" indicating prevalence of radium adsorbed onto natural solids and incorporated in insoluble rock particles. The proportion of the

"loosely bound" radium is important because it represents the radium that can be redissolved from suspended solids due to an increase in ionic strength of the water.

The ratio of the migratory forms of radionuclides in surface water is largely determined by the processes of adsorption of their dissolved forms on stream suspended solids and by its dissolution or desorption from the solids. The kinetics of these processes are poorly known since relatively few data are available on the changes observed in natural streams and even the existing data are sometimes difficult to interpret because of complicating effects of dilution and other natural processes. Specifically, coprecipitation of radium with foreign solids is possible. For instance, coprecipitation with ferric hydroxide is probable in river water receiving untreated mine drainage waters (Pradel 1976).

Among the most important natural processes affecting migration of radium in streams is sedimentation of suspended solids and resuspension of bottom sediments. Both depend strongly on the velocity and turbulence of stream flow. The nature and composition of the sediments are primary factors determining migration of radium. Pore or interstitial water represents the main migration medium. Its composition is significantly influenced by the composition of the sediments. Radium undergoes adsorption and desorption process which largely determine its distribution between the pore water and the sediments. The distribution depends also on the composition of the pore water, which can differ substantially from the composition of water overlying the sediment layer. Chemical reactions involving organic matter and minerals such as decomposition of organic matter and reduction of sulfate to sulfide, can bring about desorption/dissolution of radium, specifically, and radionuclides, in general, into the pore water or their adsorption/coprecipitation from it. The existence of a concentration gradient in the pore water is hypothesized to cause diffusional flux of the radionuclides which, in combination with the adsorption/desorption and coprecipitation/dissolution processes, can lead to their redistribution throughout the sediment layer. Higher or lower concentrations of radionuclides in sediment pore water relative to the

overlying water can establish conditions for diffusional flux that can result in their release from the sediment layer or in their concentration from the overlying water to sediments, respectively. The same processes are probable for all the naturally occurring radioisotopes, including U-238, U-235, U-234, Ra-226, Th-230, Th-232, Th-228, Ra-228 and Pb-210. Activities of the aquatic biota can also be significant in altering gradients in the near-surface sediments, through irrigation of the sediment or actual mixing and transport of the sediment particles.

1.4 Description of the Study Area

The Rabbit Lake uranium mine and mill is located in northern Saskatchewan, on the west side of Wollaston Lake (Figures 2 to 3). The sediment sampling for this project was carried out in Horseshoe Pond.

Horseshoe Pond is downstream from the precipitation ponds of the Rabbit Lake mine effluent treatment system. It has a surface area of approximately eight acres (3.2 hectares). Discharge from Horseshoe Pond enters the north end of Hidden Bay.

Duplicate sediment cores were taken at four locations equidistant from Horseshoe Pond inflow (from effluent treatment system) to the outflow (to Hidden Bay). A sediment core was also taken at Hidden Bay near the mouth of the Horseshoe Pond effluent. Surface water samples were taken at the inflow and outflow locations of Horseshoe Pond.

1.5 Methodology

1.5.1 Sample Collection

Sediment samples were collected using SCUBA. The samples were collected in 5.7 cm diameter cast acrylic tubes which were

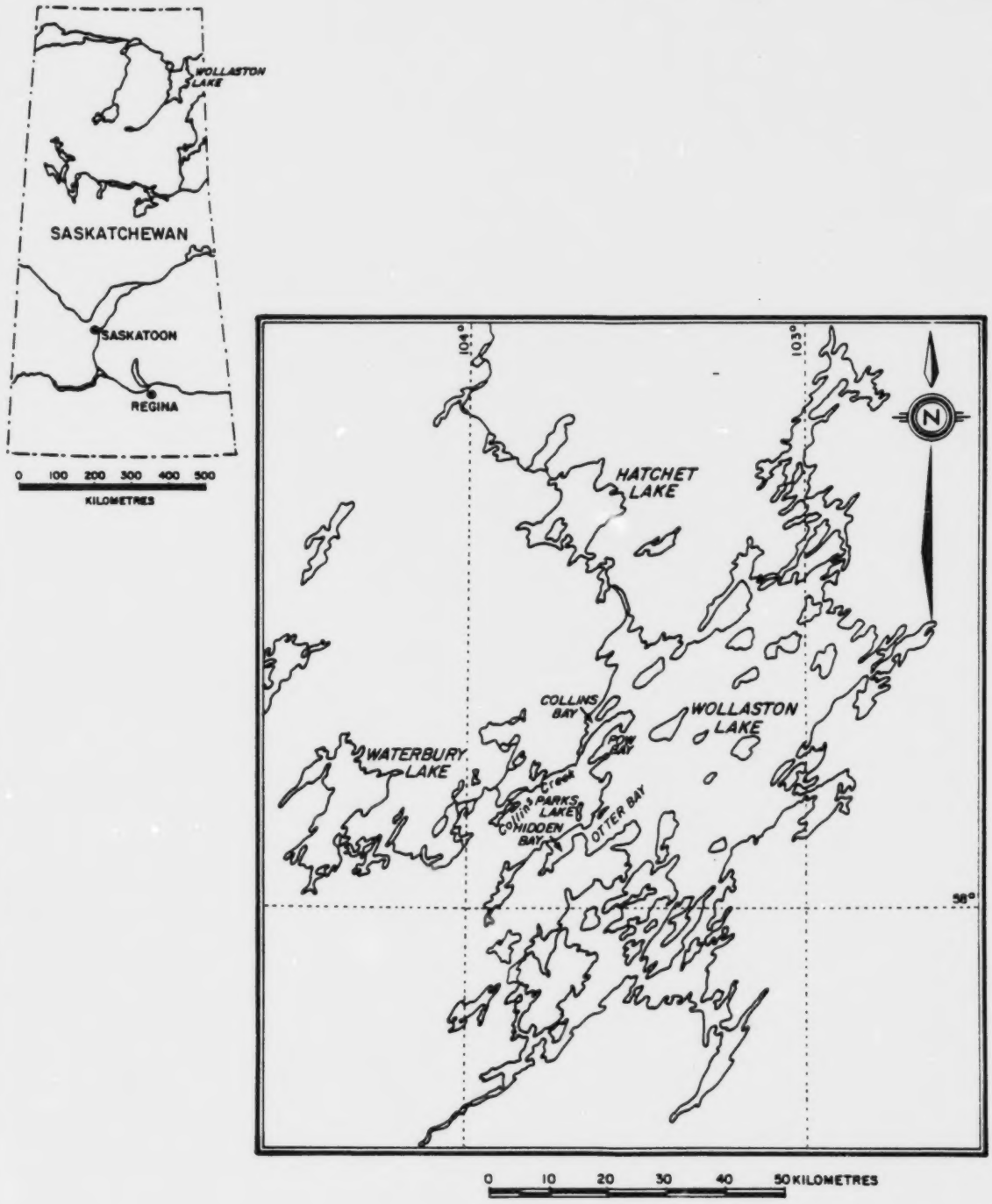


FIGURE 2
GENERAL SCHEMATIC OF STUDY AREA

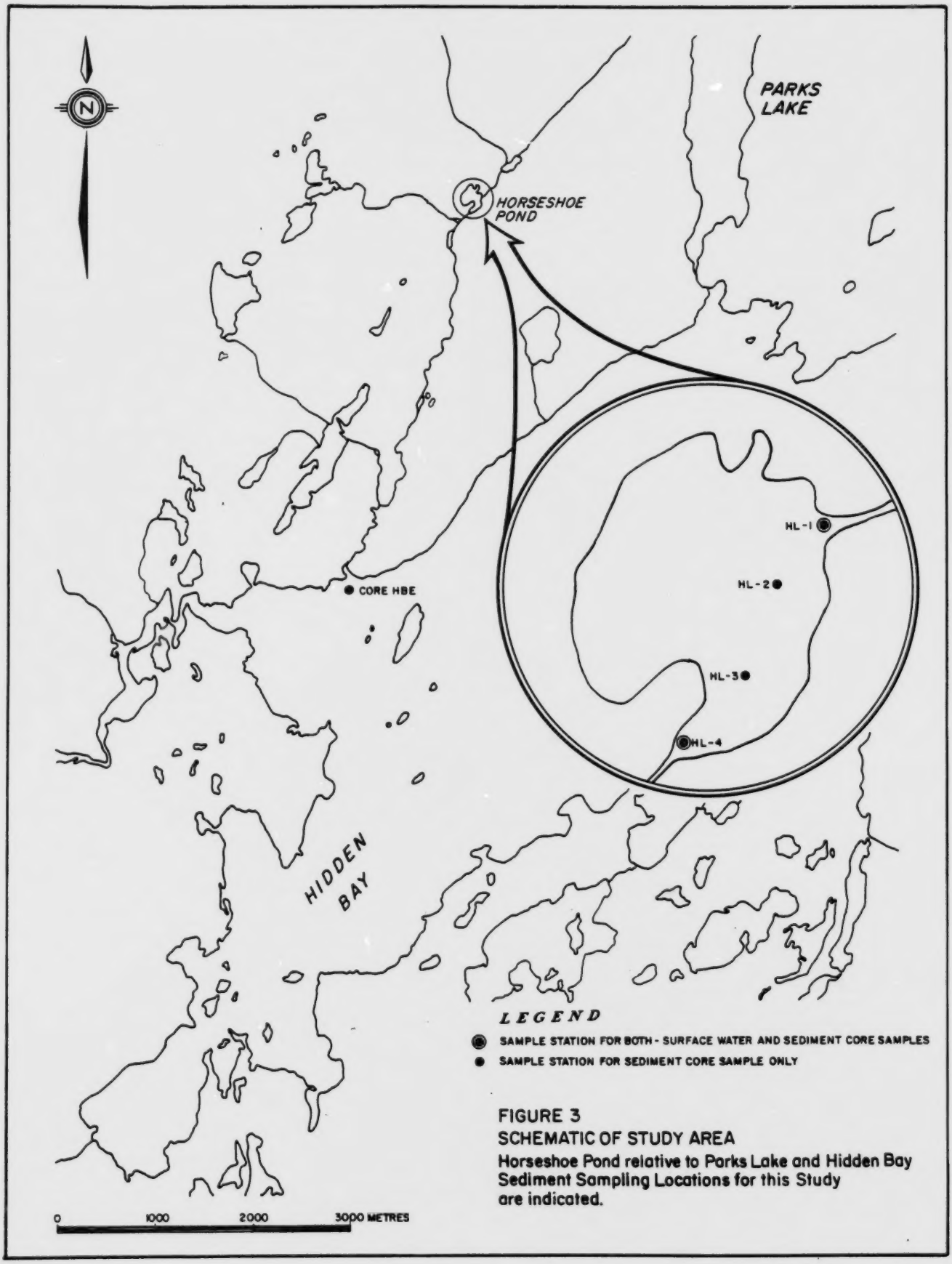


FIGURE 3
SCHEMATIC OF STUDY AREA
Horseshoe Pond relative to Parks Lake and Hidden Bay
Sediment Sampling Locations for this Study
are indicated.

slowly inserted into the sediment by hand, to minimize disturbance of the surface layers. The sediment was extruded from the core shortly after collection, and sectioned into appropriate lengths. The sections were stored in plastic bags and returned immediately to the laboratory for analysis.

At the laboratory, the interstitial water contained in each sediment section was removed by use of an air pressure filter apparatus. This water was retained for analysis. The sectioned sediment samples were weighed and then dried prior to radiochemical analysis.

1.5.2 Analytical Procedures

All radiochemical determinations made in this study were carried out as described in the NUTP Analytical Methods Manual. Uranium in water was determined using the fluorometric procedure, while in the sediment it was determined by delayed Neutron Activation Analysis (NAA). This measurement was made by Atomic Energy of Canada Limited (AECL), Commercial Products. Water quality measurements of the intersititial waters were made using Environment Canada methodologies.

After drying, the sediments were analyzed for uranium, Ra-226, Ra-228, Ra-224, Th-232, Th-230, Th-228, Pb-210 and U-234/U-238 activity ratio. Using the procedures described in the literature by Joshi et al. (1980), Joshi and Ganguly (1977), Presley et al. (1972), Willey and Fitzgerald (1980) and Kepkay (1986) the Ra-226, Ra-228, Pb-210, U-234 and U-238, bound to the sediment organics, were freed by leaching with hydrogen peroxide. The solid, inorganic, sediment remaining from the peroxide oxidation was analysed for U, Th-232, Th-230, Th-228 and Ra-226.

Procedure for the Determination of U-234/U-238 Activity Ratio in Sediments

After decomposition of the sediment samples by KF/Pyrosulfate fusion (NUTP Analytical Methods Manual, CANMET 1984), remove thorium by co-precipitation with $PbSO_4$. Add 3 mL of HNO_3, 0.4 mmole of $Al(NO_3)_3$ and 0.45 mmole of $(NH_4)_2HPO_4$ (Edwards 1968). Heat the combined solution to boiling to remove any carbon dioxide. Add NH_4OH dropwise with vigorous stirring until the pH reaches 6. Continue heating the mixture gently for thirty (30) minutes. Remove stirrer and allow the precipitate to settle. Decant supernate and transfer precipitate to a 40 mL centrifuge tube. Centrifuge and decant supernate. Dissolve precipitate in 6 mL of 3.5 M acidic $Mg(NO_3)_2$-1 M HNO_3 solution and transfer to a 25 x 150 mm test tube with the aid of 4 mL of 3.5 M $Mg(NO_3)_2$-1 M HNO_3 solution. Extract uranium twice with 10 mL portions of ethyl acetate, remove the latter by disposable pipette and transfer to a 100 mL teflon beaker. Evaporate to dryness and dissolve the residue with 5 mL IN HCl. Cool and co-precipitate uranium fluoride with cerous fluoride (Sill and Williams 1981). Filter the fluoride mixture in a 25 mm Tuffryn HT-200 filter, mount on plastic discs, dry and determine U-238 and U-234 by high resolution alpha spectrometry.

Procedure for the Separation of Organic Layer from Sediment Core by Hydrogen Peroxide Oxidation

(according to methodology described in Joshi et al. 1980, Joshi and Ganguly 1977)

Weigh, into a 250 mL beaker, 5 g of sediment sample. Add 100 mL of 0.05 M HCl and 2 mL of 30% H_2O_2. Mix the content with a stirring rod. Cool with cold water to moderate the reaction if necessary. Add more peroxide until no further reaction occurs at room temperature. Heat the beaker and its content on a hot plate, gradually, to 80 degrees C. Add more peroxide during heating until

no further reaction occurs at 80 degrees C. After cooling to room temperature, separate the aqueous layer from the sediment core by centrifugation. Wash the sediment core three times with 25 mL portions of deionized water and combine all washings with the aqueous layer.

Add 10 mL of a 1:1 mixture of HNO_3 and $HClO_4$ to the aqueous layer and evaporate to dryness. Dissolve the residue in 100 mL of 5% HCl. Take aliquots for radiochemical analysis.

Dry the inorganic sediment core in an oven at 50 to 60 degrees celsius until constant weight is attained. Take an aliquot for radiochemical analysis.

1.5.3 Quality Control

Methodology

Water quality parameters were analyzed according to the Inland Water Directorate's Analytical Method Manual (Environment Canada 1979). Radionuclides were analysed according to NUTP's Radioanalytical Method Manual (CANMET 1984). Methods for the determination of uranium activity ratio and for the separation of the sediment organic layer from inorganic core were based on procedures published in the literature (see Section 1.5.2).

Chemicals and Standards

All chemicals used were reagent grade or better. Radionuclide standard solutions were prepared by dilution from commercially available solutions. They were all obtained from reputable suppliers.

Instrument Calibration

Each analytical instrument was calibrated against standard solutions prior to the measurement of a parameter. A calibration curve was either manually generated, e.g. for the determination of sulfate and chloride using ion chromatography, or electronically, e.g. for the determination of cations using inductively coupled plasma emission spectroscopy. If there were more than ten (10) samples per batch, the calibration was repeated at least once to insure that no large deviation of instrument response had occurred during the run.

For radionuclide counting, standards were used daily to determine the counting efficiencies of the Alpha Spectrometer surface barrier detectors and the correct identification of isotopes. Background counting for each alpha spectrometer was done at least once a day.

Control Samples

Standard reference and CANMET tailings material were used as standards and controls. One or two of these materials were used per batch of twenty (20) samples. A summary of results obtained are as follows in Table 1.

Tracers

Radioactive tracers Ba-133 and Th-234 were used in every analysis of Ra-226/Ra-224 and Th-232/Th-230/Th-228 respectively. The tracers were added to an aliquot of the sample prior to the decomposition step. The amount of tracer recovered was a measure of the efficiency of the entire chemical procedure.

TABLE 1

Standard Reference Materials

Radionuclide	Reference	Activity	Results[b]	No. of Results
Ra-226	RAY.44[a]	0.99 Bq/mL	1.00 ± 0.03 Bq/mL	250
	UTS-1	3.67 Bq/g	3.70 ± 0.10 Bq/g	20
Th-228	RLZ.44[a]	1.49 Bq/mL	1.50 ± 0.10 Bq/mL	100
	UTS-1	0.71 Bq/g	0.68 ± 0.05 Bq/g	20
Th-230	UTS-1	3.60 Bq/g	3.70 ± 0.20 Bq/g	20
Th-232	UTS-1	0.68 Bq/g	0.70 ± 0.05 Bq/g	20
Pb-210	RBZ.44[a]	3.52 Bq/mL	3.60 ± 0.20 Bq/mL	150
	UTS-1	3.25 Bq/g	3.30 ± 0.20 Bq/g	20
Ra-228	$Th(NO_3)_4 \cdot 4H_2O$ in Solution[c]	4.08 Bq/mL	4.10 ± 0.20 Bq/mL	60
	UTS-1	0.68 Bq/g	0.70 ± 0.10 Bq/g	10

a These Standardized Radioactive Solutions were obtained from AMERSHAM CORPORATION. Sources prepared from these solutions are used daily to calibrate counting intrument and as standards.

b This column summarized results obtained in Monenco Lab during 1985.

c 1 mg Th per mL.

Environmental Conditions

All measurements and calibrations were carried out in an area that provides control of environmental conditions to the degree necessary to ensure required accuracy. The area was free of dust, vapours and vibration. Each instrument was not located close to equipment that produces vibration, chemical emissions or noise. The laboratory area was maintained at a temperature of 21-22 degrees Celsius. The analytical balances and electronic equipment for radiochemistry and the ICP-ES unit, for trace elements measurement, were located in an air conditioned environment. A filter air supply was provided to this area.

Preventative Maintenance

A preventative maintenance program was in effect which includes cleaning, lubricating, adjusting and testing of all instruments on a regular basis. Its purpose is to increase measurement system reliability and thus increase data reliability. The instrumentation was examined visually and electronically.

Inter-Laboratory Testing Programs

This laboratory participates in inter-laboratory testing programs organized by:

(1) Environment Canada
(2) Alberta Environment
(3) Saskatchewan Environment
(4) Western Enviro-Agricultural Laboratories Association
(5) CANMET
(6) Alberta Water Analysis Committee
(7) USEPA - Las Vegas

II. HISTORICAL STUDY AREA INFORMATION

The mining and milling of the Rabbit Lake ore body began in 1975. The earliest information available on the chemistry of Rabbit Lake and its sediments are dated as 1970 (Deju. 1970, Saskmont Ltd. 1970, Deju. 1971). In October of that year, a water balance was carried out. The surface water inflow to the lake, excluding runoff, on that date was 454 L/min (100 Igpm) and the outflow was 1362 L/min (300 Igpm). Ground water flow information is not available. The bedrock of the lake, based on a limited number of cores, was determined to be composed of conglomerate, sandstone, arkose, quartzitic limestone and metamorphic derivatives of the above. Also, in 1971, a drilling program was carried out to assess the general soil stratigraphy and ground water conditions in the Rabbit Lake area. No data concerning the chemical composition of the lake bottom sediments were obtained.

The actual dewatering of Rabbit Lake was carried out between 1971 and 1974 (Garratt 1984) by construction of a drainage channel between Rabbit Lake and Upper Link Lake. Some of the bottom sediments were also carried along and settled out in Upper Link Lake.

There have been several studies carried out concerning the composition of sediment samples in the lakes located near Rabbit Lake. The first study was carried out by Sawchyn (1973) in 1972, of sediments taken from Upper Link Lake, Lower Link Lake, Pow Bay, Parks Lake and Wollaston Lake. His data, summarized in Table 2, indicated that the lakes in the drainage system downstream from Rabbit Lake, i.e. Upper Link Lake, Lower Link Lake and Pow Bay, contained surface sediment having uranium activity more than six times greater than the activities of either thorium-230 or radium-226. Table 3 summarizes the activity ratios found by Sawchyn (1973). The lack of secular equilibrium between uranium and its immediate decay daughters suggested that the uranium found its way to these sediments primary as a result of adsorption from solution (hydromorphic transport), possible as a carbonatouranyl complex, as opposed to the alternate mechanism of deposition in the form of mineralized

TABLE 2

Analytical Data for Lake Bottom Sediments Derived from the Environmental Survey of Wollaston Lake, Saskatchewan by W.W. Sawchyn, Saskatchewan Research Council

Samples were collected in August, 1972 prior to Rabbit Lake dewatering (from Garratt 1984)

	Bq/g				
Sample Location	U-238	Th-230	Ra-226	Pb-210	Po-210
Upper Link Lake	0.80	0.06	0.11	0.08	0.03
Upper Link Lake	0.77	0.11	0.15	0.24	0.05
Upper Link Lake	1.98	0.08	0.14	0.34	0.02
Lower Link Lake	0.69	0.09	0.13	0.09	0.02
Lower Link Lake	0.68	0.08	0.08	0.14	0.01
Pow Bay	1.93	0.22	0.28	0.46	0.12
Hidden Bay 1	0.15	0.05	0.02	0.11	0.01
Hidden Bay 2	0.06	0.08	0.11	0.26	0.08
Hidden Bay 3	0.07	0.06	0.06	0.48	0.11
Hidden Bay 4	0.04	0.07	0.12	0.19	0.02
Parks Lake	0.05	0.05	0.02	0.04	0.03

TABLE 3

Activity Ratios in Sediments of Rabbit Lake Drainage System
as Reported by Sawchyn in 1973
(Calculated from data contained in Table 2)

Sample Location	$\frac{\text{U-238}}{\text{Ra-226}}$	$\frac{\text{Ra-226}}{\text{Th-230}}$	$\frac{\text{Pb-210}}{\text{Ra-226}}$
Upper Link Lake	7.3	1.8	0.7
Upper Link Lake	5.1	1.4	1.6
Upper Link Lake	14.1	1.7	2.4
Lower Link Lake	5.3	1.4	0.7
Lower Link Lake	8.5	1.0	1.7
Pow Bay	6.9	1.3	1.6
Hidden Bay 1	7.5	0.4	5.5
Hidden Bay 2	0.5	1.4	2.4
Hidden Bay 3	1.2	1.0	8.0
Hidden Bay 4	0.3	1.7	1.6
Parks Lake	2.5	0.4	2.0

solids. It is interesting to note that the other two lake sediment samples studies by Sawchyn, taken from Hidden Bay and Parks Lake, did not show uranium activity in as large an excess. This suggests that, in those two locations, the hydromorphic transport mechanism for uranium was not taking place to the same extent. The presence of unsupported Pb-210, in most of the lake sediments studied, may be due to atmospheric fallout and the radon-222 emanation mechanism.

In 1974, Cameron and Ballantyne (1977) surveyed sediments from the vicinity of Rabbit Lake. At that time, the lake was almost completely drained, but had not been excavated for mining. These data, shown in Table 4, are believed (Garratt 1984) to reflect sediment levels uninfluenced by human activities. Data relating the degree of secular equilibrium between uranium and its descendents were not provided, but the levels of uranium activity reported in Upper Link Lake (1.4 Bq/g) and Lower Link Lake (0.82 Bq/g) sediments were of the same order of magnitude as those measured by Sawchyn in 1972. These workers found a strong correlation between the uranium contained in the sediment and the uranium content of the waters of the lakes in the area. No correlation was found between the LOI and the uranium content of lake sediments in the area. Cameron and Ballantyne also plotted the uranium content of the lake sediments in the area. This plot confirmed the findings of Sawchyn that the highest uranium contents of lake sediment were observed in Rabbit Lake and the downstream lakes, Upper and Lower Link Lakes and Pow Bay. The data also suggested that the draining of Rabbit Lake had not dramatically altered the Upper Link Lake sediment from its natural composition. Rather, the high levels of uranium are considered by Garratt (1984) to give further evidence of the active oxidation and dispersion of uranium from the main Rabbit Lake deposits, transported by ground water and hydromorphically deposited in the Rabbit Lake drainage system. The high levels of uranium activity in lake sediment, relative to the activities of its descendents, were also noted by Garratt in the vicinity of two other known mineralized zones, located in Saskatchewan (Hab Mine area and Seahorse Lake).

TABLE 4

Analytical Data for Lake Bottom Sediments Derived from the Reconnaissance Survey by E.M. Cameron and S.B. Ballantyne, Geological Survey of Canada. Samples Collected September, 1974 (from Garratt 1984).

Sample Location	U-238, Bq/g	LOI, %
Rabbit Lake, north shore	5.93	44.4
Rabbit Lake, south shore	7.02	43.8
Upper Link Lake	1.4	24.8
Lower Link Lake	0.82	19.0
Pow Bay	0.05	4.4

The influence of mining and milling operations on lake sediments is usually indicated by activity levels of Th-230 and Ra-226 that are equal to, or exceed, the U-238 activity. Because thorium is insoluble under normal water quality conditions, its presence is evidence of the mixing of the natural lake sediment with the mill tailings or mined ore. The activity equilibrium between Ra-226 and Th-230 is further evidence of the deposition of clastic material. Where mine tailings or eroded ore particles are deposited, the activity level of thorium-230 usually approaches that of radium-226 in the sediment. This was noted by Garratt (1984) in sediments obtained from Marie and Fookes Lake, both of which are tailings lakes within the waste management system for the, now closed, Beaverlodge operations. His data are shown in Table 5. A summary of U-238/Ra-226 and Ra-226/Th-230 activity ratios for the data contained in Table 5 is given in Table 6.

2.1 Influence of Rabbit Lake Mining on Upper Link Lake Sediments

Since the dewatering of Rabbit Lake took place between 1971 and 1974, it has been suggested by Garratt (1984) that the radiochemical data of Sawchyn (1973) (three samples analyzed in 1972) and Cameron/Ballantyne (1977) (one sample analyzed in 1974) may indicate that the uranium and radium-226 contents of the Upper Link Lake sediments were not increased, substantially, by the dewatering of Rabbit Lake. The mining at Rabbit Lake began in mid 1975. Between the summers of 1975 and 1977, mine drainage containing relatively high levels of uranium and radium-226 were pumped into Upper Link Lake. In 1980, Saskmont Engineering Limited (Saskmont Ltd. 1980) examined, in detail, the sediment of Upper Link Lake, Horseshoe Pond, Hidden Bay and Pow Bay. Their radiochemical data, including organic carbon content determined by potassium dichromate oxidation (Allison 1965), are shown in Table 7 and plotted as a function of sediment depth in Figure 4. In Hidden Bay (Figure 4C), Horseshoe Pond (Figure 4B), and Pow Bay (Figure 4D), the activity levels for U-238 and Ra-226 in the sediments, were as expected from earlier studies (Knight 1971, Cameron et al. 1977) in the area. However, the surface sediment from Upper Link Lake (Figure 4A) was distinctive in having extremely

TABLE 5

Radiochemical Data on Lake Sediments Taken Downstream from the Beverlodge, Saskatchewan Mining and Milling Operation. (Taken from Garratt 1984)

Sample Location	U-238, Bq/g	Th-230, Bq/g	Ra-226, Bq/g
Fookes Lake	1.48	33.1	47.1
Fookes Lake	1.61	31.4	42.6
Marie Lake	3.09	0.92	0.1
Marie Lake	6.18	33.7	46.4
Marie Lake	4.70	45.2	61.8
Marie Lake	23.50	41.2	39.7

TABLE 6

Activity Ratios in Sediments Taken Near
Beaverlodge Mining Operation by Garratt (1984)
(Calculated from Data Contained in Table 5)

Sample Location	$\frac{\text{U-238}}{\text{Ra-226}}$	$\frac{\text{Ra-226}}{\text{Th-230}}$
Fookes Lake	0.03	1.4
Fookes Lake	0.04	1.4
Marie Lake	28.09	0.1
Marie Lake	0.13	1.4
Marie Lake	0.08	1.4
Marie Lake	0.59	1.0

TABLE 7 Radionuclide levels in Sediment Cores from Rabbit Lake Area 1980 (taken from Saskmont.1980)

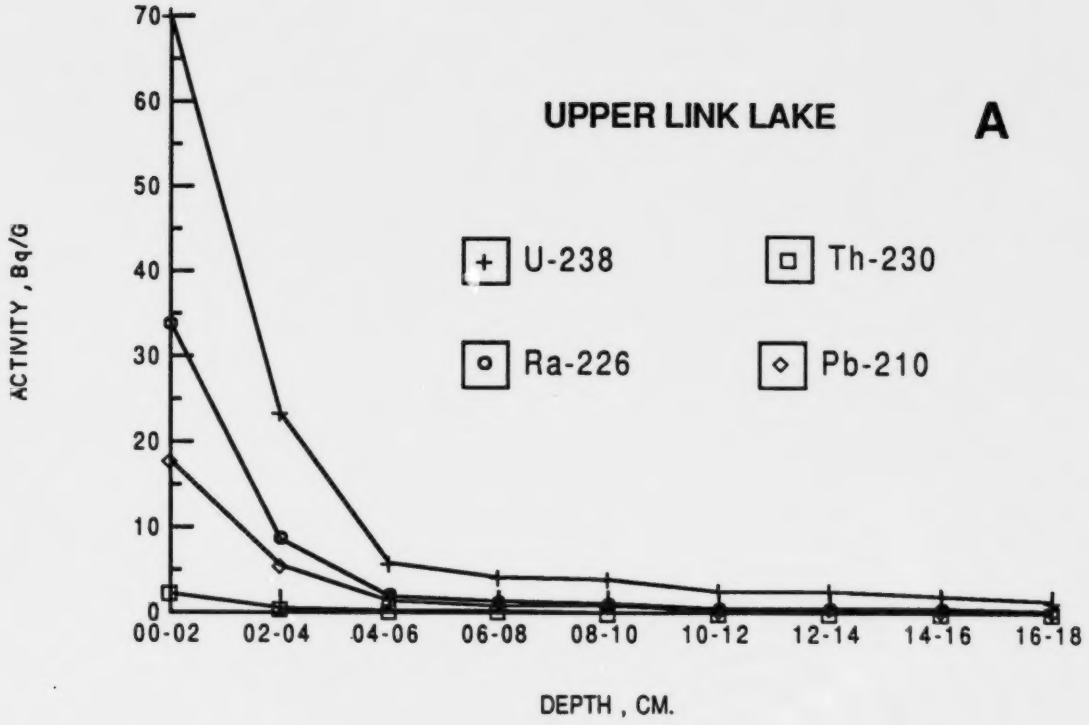
Depth, cm.	U,ug/g	Bq/g (dried weight) U-238	Th-230	Ra-226	Pb-210	Organic carbon*,%
	UPPER LINK LAKE					
00-02	5650	69.9	2.3	17.8	34	8.2
02-04	1890	23.4	0.48	5.6	8.5	9.6
04-06	464	5.7	0.28	1.4	1.9	15.1
06-08	328	4.1	0.31	0.96	1.3	11.7
08-10	307	3.8	0.07	0.78	1.1	12.1
10-12	191	2.4	0.02	0.41	0.63	11.6
12-14	196	2.4	0.03	0.44	0.67	15.0
14-16	149	1.8	0.04	0.36	0.45	22.0
16-18	123	1.5	0.02	0.17	0.18	22.2
	HORSESHOE POND					
00-04	53.5	0.662	0.02	0.09	0.08	5.3
04-06	3.2	0.040	0.02	0.03	0.06	1.7
06-08	2	0.025	0.02	0.03	0.02	1.5
08-10	1.7	0.021	0.02	0.02	0.07	1.1
10-12	1.6	0.020	0.02	0.02	0.07	1.6
	HIDDEN BAY					
00-02	326	4.03	0.02	0.04	0.20	10.4
02-05	167	2.07	0.02	0.08	0.11	7.5
05-10	35.7	0.44	0.02	0.02	0.05	3.5
	POW BAY					
00-02	9.1	0.11	0.02	0.07	0.23	1.7
02-05	3.3	0.041	0.02	0.04	0.07	2.6
05-10	2.8	0.035	0.02	0.02	0.07	1.0
10-15	2.8	0.035	0.02	0.02	0.06	0.6
15-20	2.3	0.028	0.02	0.03	0.02	0.8

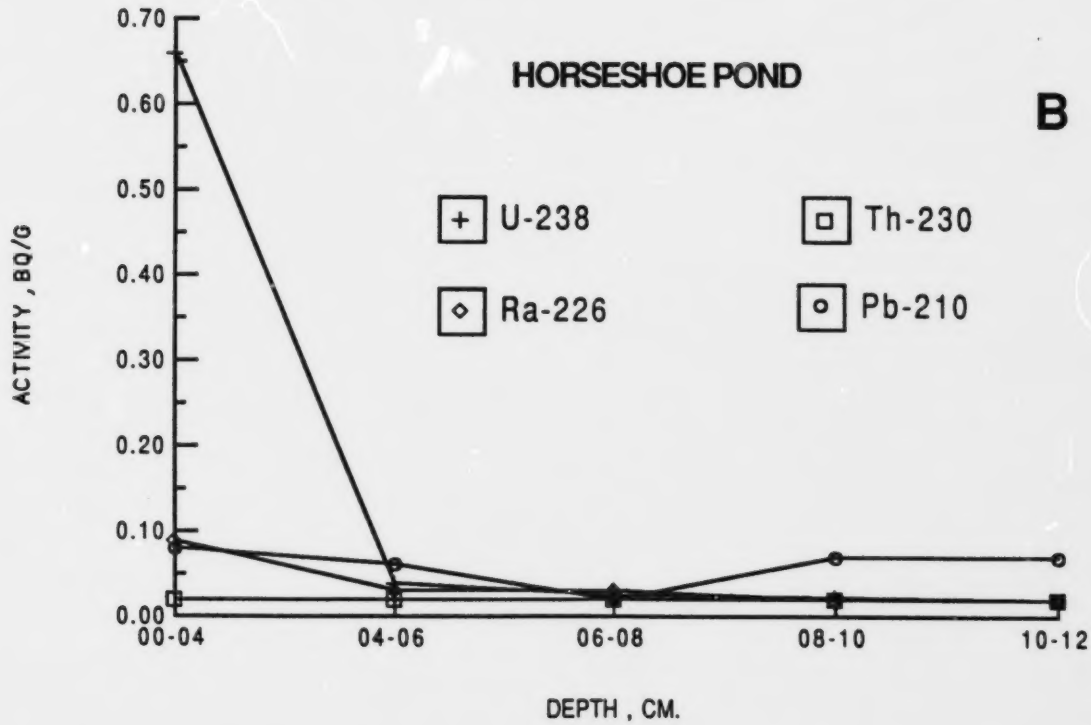
* determined by potassium dichromate oxidation

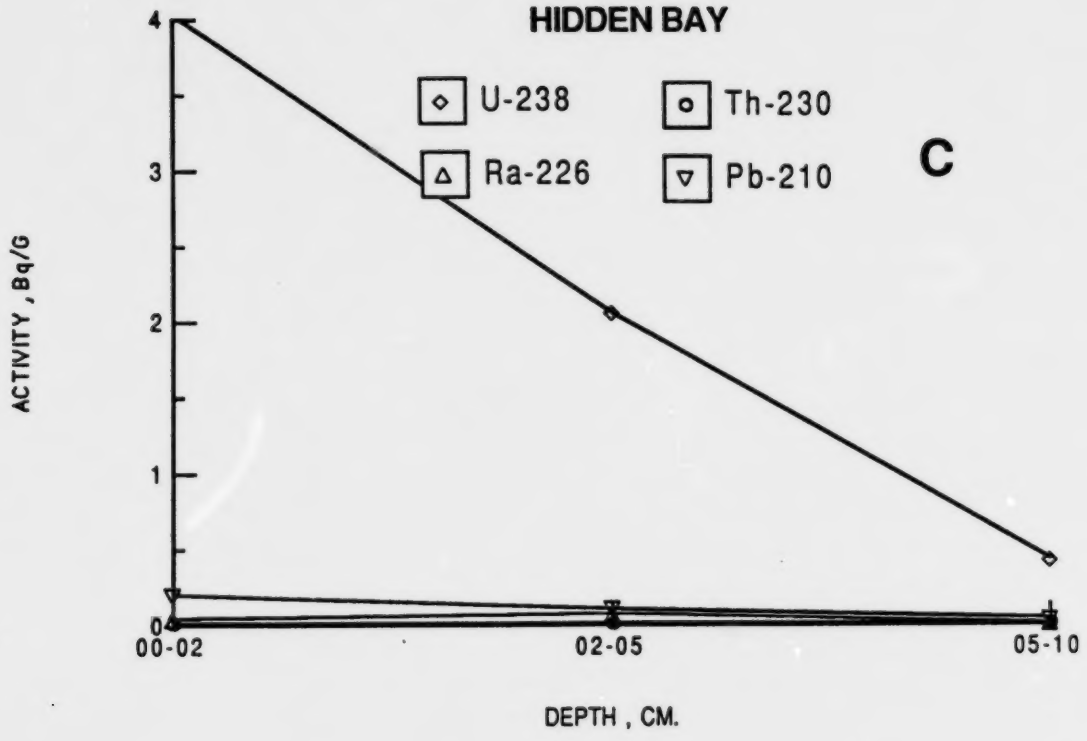
FIGURE 4

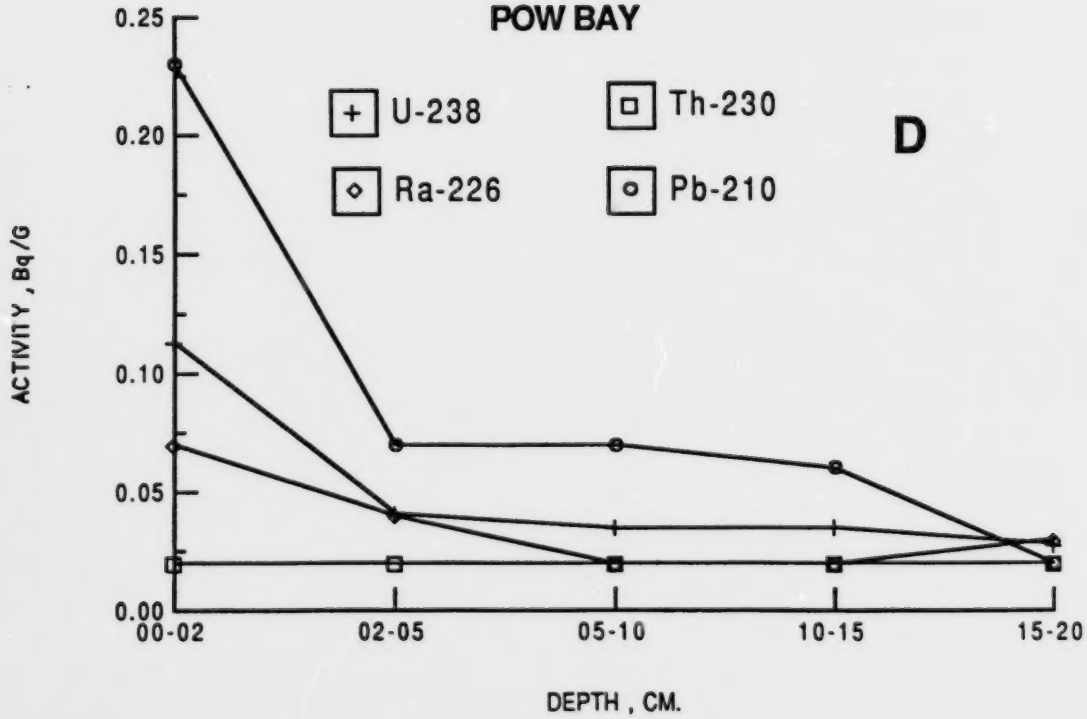
Radionuclide Contents of Lake Sediment Plotted as a
Function of Sediment Depth, 1980 data
(Taken from Saskmont 1980)

A - Upper Link Lake
B - Horseshoe Pond
C - Hidden Bay
D - Pow Bay


UPPER LINK LAKE
A
U-238
Th-230
Ra-226
Pb-210
ACTIVITY , Bq/G
70
60
50
40
30
20
10
0
00-02
02-04
04-06
06-08
08-10
10-12
12-14
14-16
16-18
DEPTH , CM.


HORSESHOE POND
B
U-238
Th-230
Ra-226
Pb-210
ACTIVITY , BQ/G
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
00-04
04-06
06-08
08-10
10-12
DEPTH , CM.


HIDDEN BAY
U-238
Th-230
Ra-226
Pb-210
C
ACTIVITY , Bq/G
4
3
2
1
0
00-02
02-05
05-10
DEPTH , CM.


POW BAY
U-238
Th-230
Ra-226
Pb-210
D
ACTIVITY , Bq/G
0.25
0.20
0.15
0.10
0.05
0.00
00-02
02-05
05-10
10-15
15-20
DEPTH , CM.

high radionuclide activities. The activities declined with depth but, at the surface, the level for U-238 was more than 50 times above those found by Sawchyn (1973) in 1972 and Cameron/Ballantyne (1977) in 1974. These findings suggest that the influence of the mining operations had become evident. Only at a sediment depth of more than 6 centimeters, did the activity level of U-238 and Ra-226 approach the levels found in 1972 (Sawchyn 1973) and 1974 (Cameron and Ballantyne 1977) suggesting that the sediment between 10 centimeters and the surface show the effects of the mining operation. The lower activity of Th-230 relative to Ra-226 and U-238 suggests that these effects were the result of hydromorphic rather than clastic deposition. It is likely that, in the Upper Link Lake sediment core sample, the sediment between 10 centimeters and the surface had its origin in Rabbit Lake (resulting from the dewatering), although in-situ hydromorphic adsorption resulting from the subsequent mining operation runoff cannot be discounted.

The activity ratios, present in the 1980 sediments taken from Horseshoe Pond, Hidden Bay, Pow Bay and Upper Link Lake sediments, are presented in Table 8 and plotted in Figure 5 as a function of depth. The variation in organic carbon content as a function of depth is also included in Figure 5. Several observations are possible.

(1) Horseshoe Pond

In the first 4 centimeters of sediment, the U-238 activity was 7 time greater than the Ra-226 activity. In addition, the Ra-226 activity exceeds the Th-230 activity by almost a factor of 5. Since, during terrestrial erosion, it is expected that U-238, Th-230 and Ra-226 would travel together in the solid phase, it may be concluded that the excess of U-238 and Ra-226 was a result of adsorption (hydromorphic deposit) from solution. The presence, of near secular, activity equilibrium between U-238 and Ra-226 and between Ra-226 and Th-230 at depth greater than 6 centimeters may be taken as possible indication that the clastic deposition mechanism predominated. The presence of excess organic carbon in the first

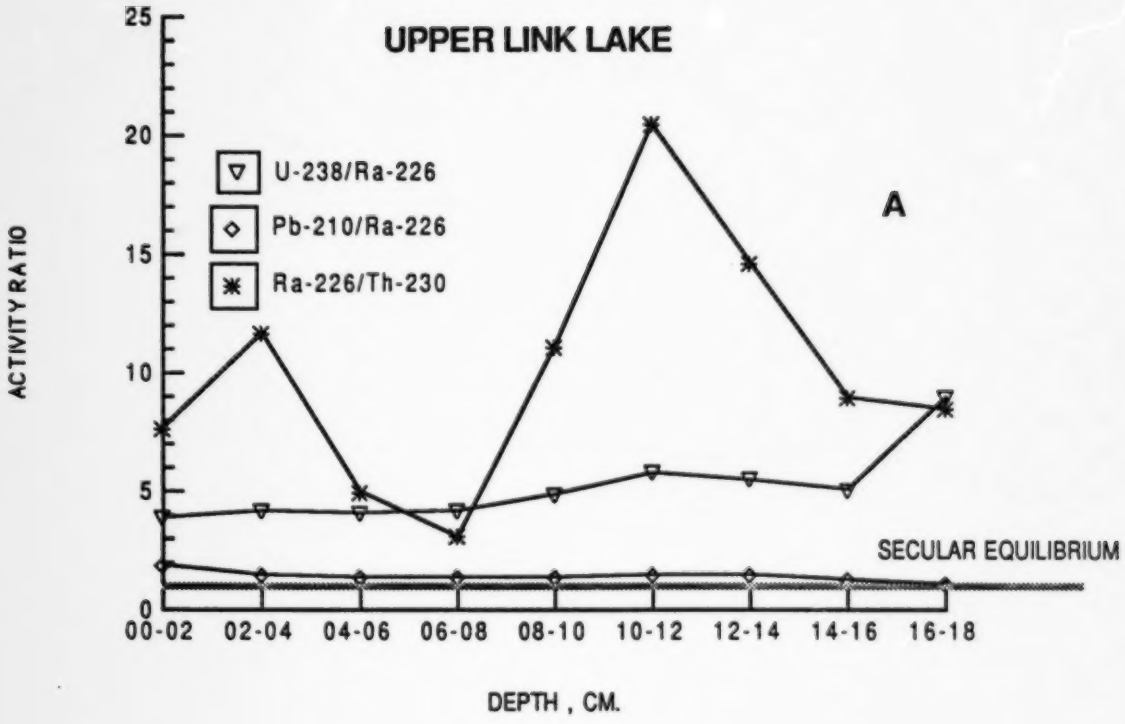
TABLE 8 - Activity ratios (calculated from TABLE 7)

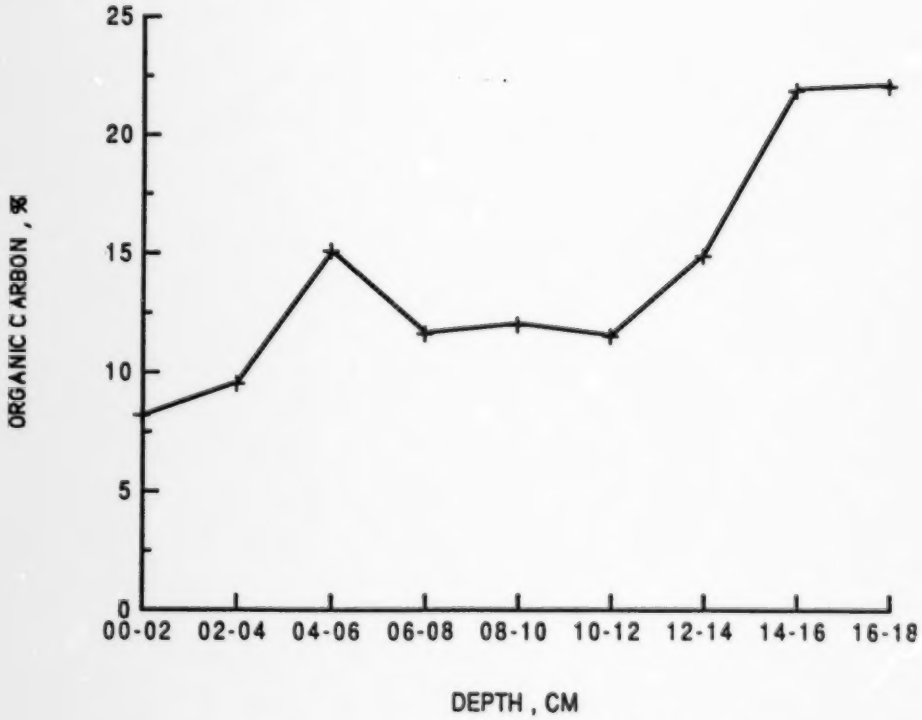
Depth, cm.	------ACTIVITY RATIO------- U-238 / Ra-226	Ra-226 / Th-230	Pb-210 / Ra-226
	UPPER LINK LAKE		
00-02	3.9	7.7	1.91
02-04	4.2	11.7	1.52
04-06	4.1	5.0	1.36
06-08	4.2	3.1	1.35
08-10	4.9	11.1	1.41
10-12	5.8	20.5	1.54
12-14	5.5	14.7	1.52
14-16	5.1	9.0	1.25
16-18	9.0	8.5	1.06
	HORSESHOE POND		
00-04	7.4	4.5	0.89
04-06	1.3	1.5	2.00
06-08	0.8	1.5	0.67
08-10	1.1	1.0	3.50
10-12	1.0	1.0	3.50
	HIDDEN BAY		
00-02	101	2.0	5.00
02-05	26	4.0	1.38
05-10	22	1.0	2.50
	POW BAY		
00-02	1.6	3.5	3.29
02-05	1.0	2.0	1.75
05-10	1.7	1.0	3.50
10-15	1.7	1.0	3.00
15-20	0.9	1.5	0.67

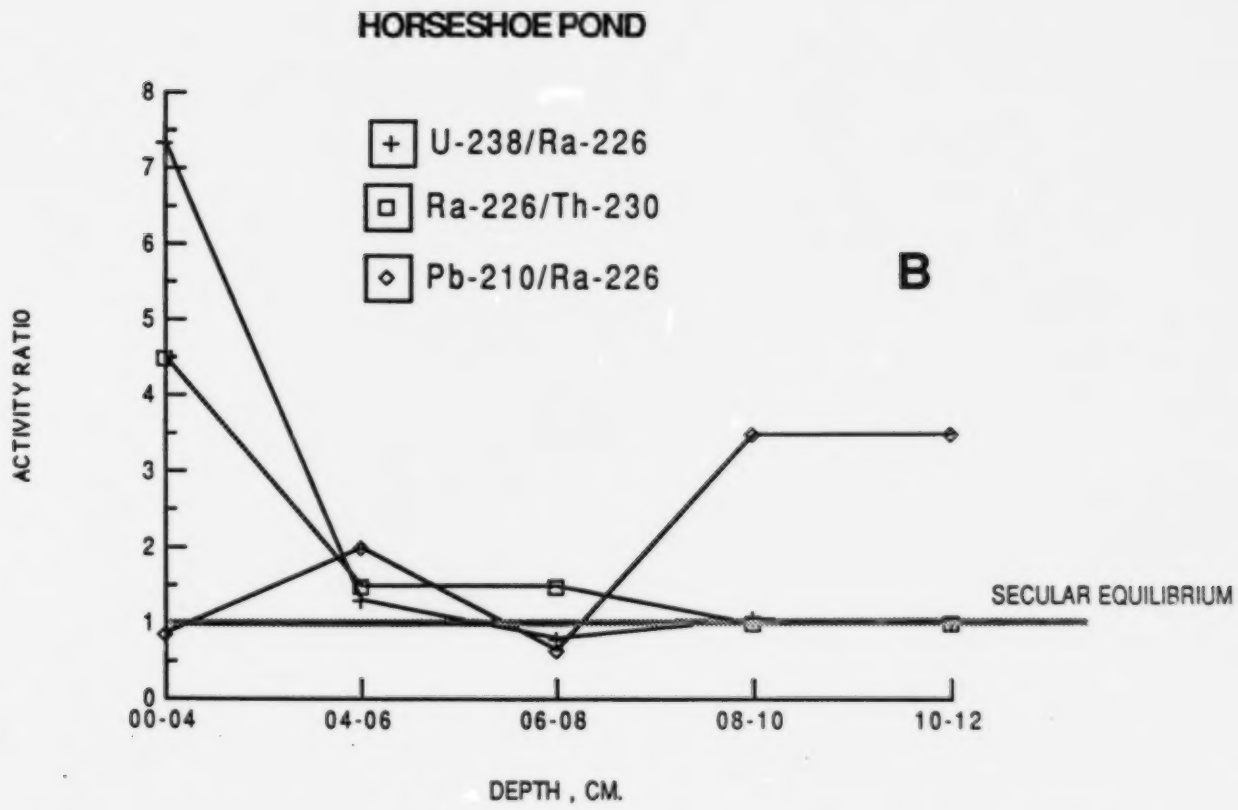
FIGURE 5

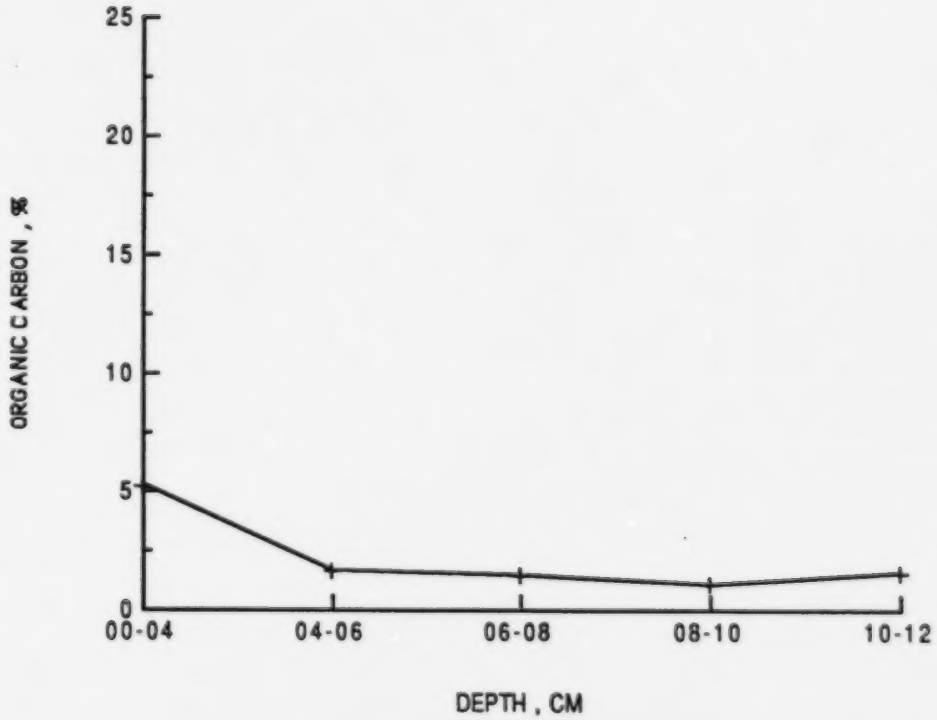
Activity Ratio and Organic Carbon Contents of Lake Sediment
Plotted as a Function of Depth, 1980 data

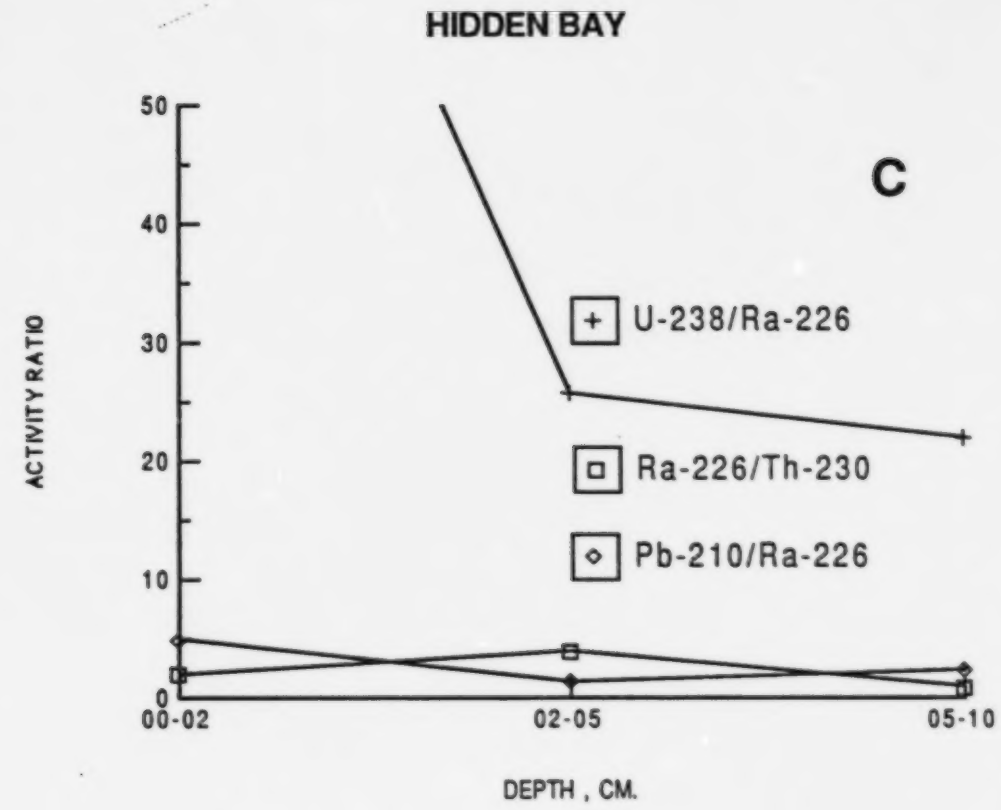
A - Upper Link Lake
B - Horseshoe Pond
C - Hidden Bay
D - Pow Bay

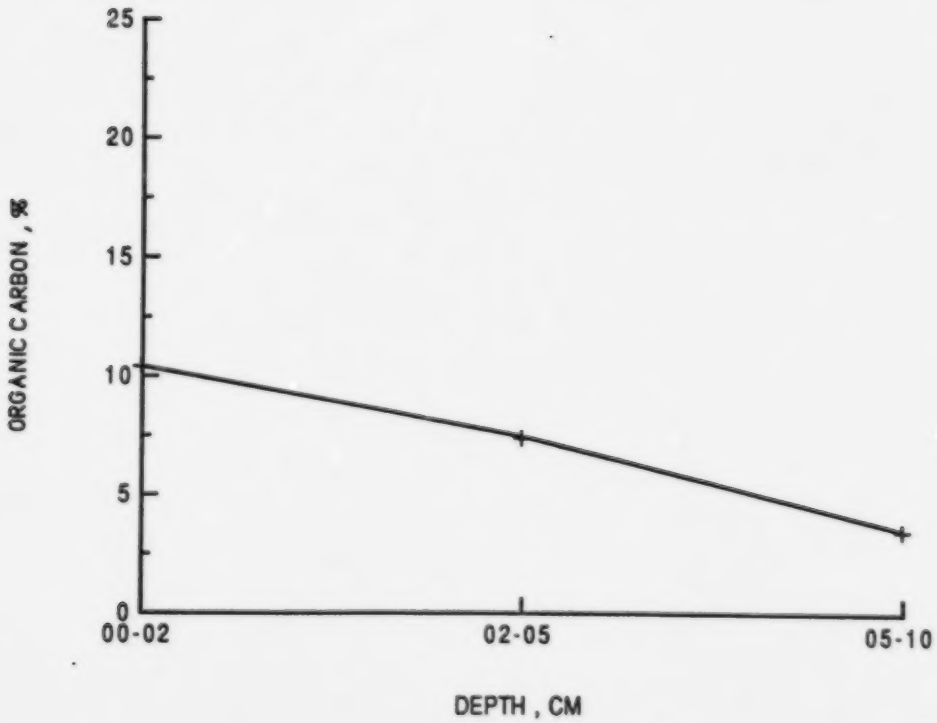

UPPER LINK LAKE
A
U-238/Ra-226
Pb-210/Ra-226
Ra-226/Th-230
SECULAR EQUILIBRIUM
ACTIVITY RATIO
25
20
15
10
5
0
00-02
02-04
04-06
06-08
08-10
10-12
12-14
14-16
16-18
DEPTH , CM.

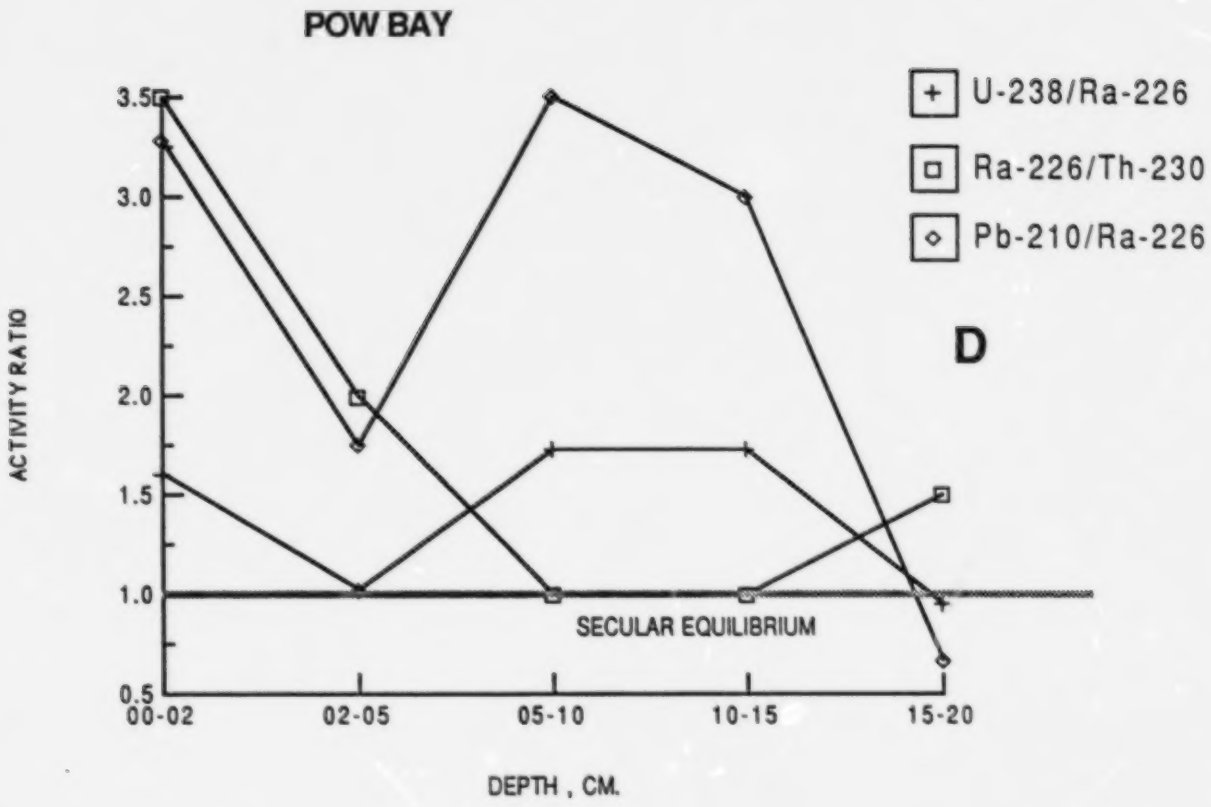

ORGANIC C ARBON , %
25
20
15
10
5
0
00-02
02-04
04-06
06-08
08-10
10-12
12-14
14-16
16-18
DEPTH , CM

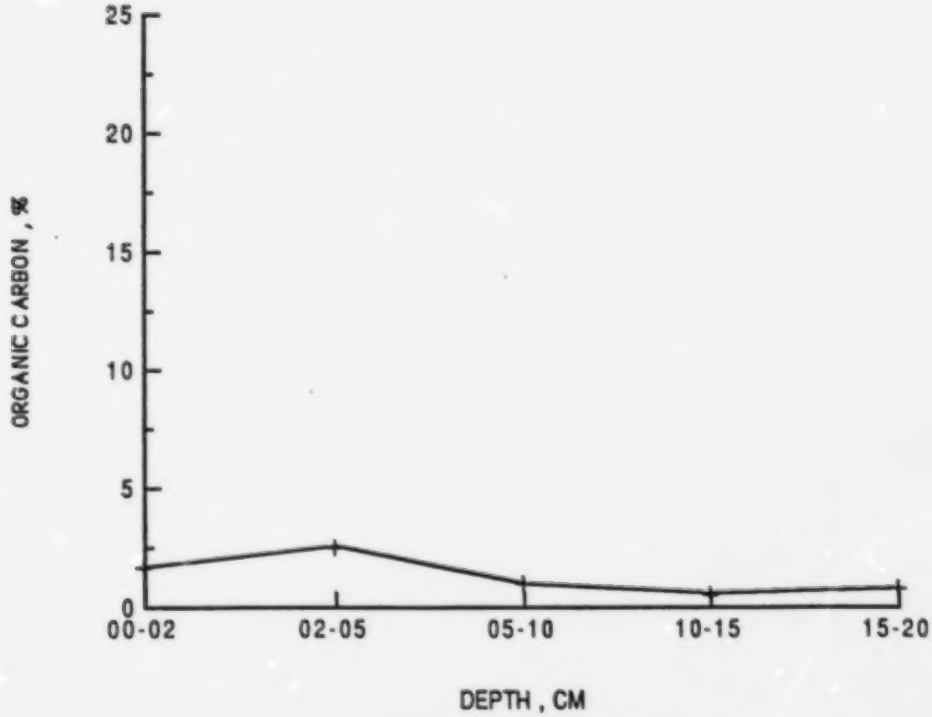

HORSESHOE POND
U-238/Ra-226
Ra-226/Th-230
Pb-210/Ra-226
B
ACTIVITY RATIO
SECULAR EQUILIBRIUM
0
1
2
3
4
5
6
7
8
00-04
04-06
06-08
08-10
10-12
DEPTH , CM.


ORGANIC CARBON , %
0
5
10
15
20
25
00-04
04-06
06-08
08-10
10-12
DEPTH , CM


HIDDEN BAY
C
ACTIVITY RATIO
50
40
30
20
10
0
U-238/Ra-226
Ra-226/Th-230
Pb-210/Ra-226
00-02
02-05
05-10
DEPTH , CM.


ORGANIC CARBON , %
25
20
15
10
5
0
00-02
02-05
05-10
DEPTH , CM


POW BAY
U-238/Ra-226
Ra-226/Th-230
Pb-210/Ra-226
D
ACTIVITY RATIO
3.5
3.0
2.5
2.0
1.5
1.0
0.5
SECULAR EQUILIBRIUM
00-02
02-05
05-10
10-15
15-20
DEPTH , CM.


ORGANIC CARBON , %
25
20
15
10
5
0
00-02
02-05
05-10
10-15
15-20
DEPTH , CM

4 centimeters, relative to the deeper depths, provides a support medium for adsorption of uranium from solution.

(2) Hidden Bay

Here, the activity ratio of U-238/Ra-226 exceeds 20 to a depth of at least 10 centimeters. While it appears that the hydromorphic adsorption mechanism has also taken place here, the levels of U-238 and Ra-226 relative to the Th-230 suggest that more adsorption (than in Horseshoe Pond) of uranium from solution has taken place and to a depth that appears to approach more than 5 centimeters. The concentration of organic carbon content as a function of depth (see Table 7) is more constant here than in Horseshoe Pond and may help explain these differences.

(3) Pow Bay

The sediment core taken from Pow Bay is similar to the core from Horseshoe Pond in that it contained very little organic carbon, and the U-238/Ra-226 and Ra-226/Th-230 activity ratios were correspondingly closer to 1.0.

(4) Upper Link Lake

The sediment core from this lake was unlike the cores from the three locations discussed above. For one thing, the organic carbon content increased with depth, but the activities of U-238, Th-230, Ra-226 and Pb-210 decreased with depth. From the surface to 18 centimeters, the activity ratios were strongly in favour of U-238 and Ra-226 relative to Th-230, suggesting that significant hydromorphic adsorption has occurred at all depths. The differences that exist between the radiochemistry content of this sediment core and the cores from the other three lakes may be taken as an indication

that the actions of the Rabbit Lake mining operation had altered Upper Link Lake sediments.

In 1981, a second sediment core study, concentrating on Upper Link Lake, was carried out by Saskmont Engineering Limited. Four sediment core samples were analyzed for uranium and Ra-226 contents. Those data are shown on Table 9 and plotted as a function of depth in Figure 6. For cores 28A, 30A and 31A, close similarities with the 1980 Upper Link Lake data (Figure 4A) are noticeable. In all instances, the major radioactivity was contained within the first 6 to 8 centimeters. Figure 7 is a plot of U-238/Ra-226 versus depth. One major difference from the 1980 data is noticeable. In the 1980 sediment core (Figure 5A), U-238/Ra-226 was consistently between 4 and 5. That, coupled with the high Ra-226/Th-230 ratio, was taken as indicative of the hydromorphic adsorption solution mechanism. In the 1981 data, the U-238/Ra-226 ratios in Upper Link Lake are generally less than 1.0 over the first four (4) centimeters. With the limited amount of radionuclide data available, an explanation for this difference between 1980 and 1981 would be highly speculative. One of the cores, 28A, was analyzed for Th-230 and Loss on Ignition (LOI). The LOI was a relative indication of the organic matter content (for an experimental comparison between LOI and organic carbon determined by dichromate oxidation see Table 20, Page III-40). The results are shown in Table 10 and tend to give a better picture of the situation. Down to a depth of seven centimeters, the close agreement between Ra-226 and Th-230 and the depletion of U-238 relative to both, suggests that the source is primarily inorganic clastic deposit resulting from the nearby mining operation (Figure 8 is a plot of activity ratios and organic matter (LOI) versus depth). This hypothesis is supported by the low LOI values in the first 7 centimeters. Between 7 and 11 centimeters, the organic matter content increased by a factor of 10. It may be significant that over this interval, the U-238 and Ra-226 activities, relative to Th-230 also increased dramatically. In 1972 and 1974, Sawchyn and Cameron/Ballantyne (1977) found an LOI of 24.8% and a U-238 activity of between 0.8 and 2 Bq/g. The Saskmont Ltd. data contained in Table 10 show that at between 9 and 10 centimeters, the U-238 was much higher, at 14 Bq/g, whereas the LOI agreed with the 1974 value of 27.9%.

TABLE 9 Radionuclide levels in sediment cores from Upper LInk Lake as per Saskmont Ltd. interim report on the investigation of radionuclide levels in the Rabbit Lake drainage system, March,1982(Saskmont.1982)(taken from Garratt.1984)Precision data taken from Saskmont.

DEPTH , CM	U,ug/gm	-Bq/g(dried weight)- U-238 (calculated)	Ra-226
LOCATION 28A			
0-2	3320 +/- 10	41.1 +/- 0.1	80 +/- 3
2-3	4860 +/- 10	60.1 +/- 0.1	91 +/- 4
3-4	3760 +/- 10	46.5 +/- 0.1	68 +/- 3
4-5	3600 +/- 10	44.5 +/- 0.1	50 +/- 2
5-6	1600 +/- 10	19.8 +/- 0.1	29 +/- 1
6-7	1800 +/- 10	22.3 +/- 0.1	24 +/- 1
7-8	2110 +/- 10	26.1 +/- 0.1	10.3 +/- 0.4
8-9	1980 +/- 10	24.5 +/- 0.1	9.6 +/- 0.4
9-10	1150 +/- 10	14.2 +/- 0.1	12.7 +/- 0.6
10-11	1690 +/- 10	20.9 +/- 0.1	31 +/- 1
11-12	2160 +/- 10	26.7 +/- 0.1	40 +/- 2
12-14	1540 +/- 10	19.1 +/- 0.1	17.2 +/- 0.7
14-16	438 +/- 1	5.41 +/- 0.01	4.7 +/- 0.2
16-18	475 +/- 1	5.88 +/- 0.01	3.1 +/- 0.2
18-20	886 +/- 1	10.96 +/- 0.01	5.4 +/- 0.2
20-22	501 +/- 1	6.20 +/- 0.01	2.5 +/- 0.1
LOCATION 29A			
0-1	889 +/- 1	11.00 +/- 0.01	13.1 +/- 0.5
1-2	521 +/- 1	6.44 +/- 0.01	9.3 +/- 0.3
2-3	526 +/- 1	6.51 +/- 0.01	10.9 +/- 0.4
3-4	1120 +/- 10	13.9 +/- 0.1	20.6 +/- 0.6
4-5	1060 +/- 10	13.1 +/- 0.1	22.8 +/- 0.9
5-6	722 +/- 1	8.93 +/- 0.01	16.1 +/- 0.5
6-7	594 +/- 1	7.35 +/- 0.01	15.3 +/- 0.4
7-8	414 +/- 1	5.12 +/- 0.01	11.6 +/- 0.4
8-9	274 +/- 1	3.39 +/- 0.01	8.6 +/- 0.3
9-10	382 +/- 1	4.73 +/- 0.01	11.6 +/- 0.4
10-12	347 +/- 1	4.29 +/- 0.01	9.9 +/- 0.3
12-14	234 +/- 1	2.89 +/- 0.01	4.6 +/- 0.2
14-16	119 +/- 1	1.47 +/- 0.01	2.7 +/- 0.1
16-18	215 +/- 1	2.66 +/- 0.01	3.0 +/- 0.1
18-20	144 +/- 1	1.78 +/- 0.01	2.0 +/- 0.1
20-25	164 +/- 1	2.03 +/- 0.01	1.3 +/- 0.1

TABLE 9 (CONTINUED)

DEPTH , CM	U,ug/g	-Bq/g(dried weight)- U-238 (calculated)	Ra-226
LOCATION 30A			
0-1	2850 +/- 10	35.3 +/- 0.1	35 +/- 1
1-2	3270 +/- 10	40.5 +/- 0.1	35 +/- 1
2-3	3230 +/- 10	40.0 +/- 0.1	37 +/- 1
3-4	2530 +/- 10	31.3 +/- 0.1	28.3 +/- 0.8
4-5	1820 +/- 10	22.5 +/- 0.1	13.3 +/- 0.5
5-6	1370 +/- 10	16.9 +/- 0.1	6.2 +/- 0.3
6-7	340 +/- 1	4.21 +/- 0.01	1.8 +/- 0.1
8-9	173 +/- 1	2.14 +/- 0.01	0.9 +/- 0.1
9-10	304 +/- 1	3.76 +/- 0.01	1.6 +/- 0.1
10-12	348 +/- 1	4.30 +/- 0.01	2.3 +/- 0.1
12-14	312 +/- 1	3.86 +/- 0.01	2.0 +/- 0.1
LOCATION 31A			
0-1	5520 +/- 10	68.3 +/- 0.1	39 +/- 1
1-2	5040 +/- 10	62.3 +/- 0.1	32 +/- 1
2-3	4140 +/- 10	51.2 +/- 0.1	24.3 +/- 0.7
3-4	1200 +/- 10	14.8 +/- 0.1	6.0 +/- 0.3
4-5	719 +/- 1	8.89 +/- 0.01	3.3 +/- 0.1
5-6	491 +/- 1	6.07 +/- 0.01	2.1 +/- 0.1
6-7	IS	IS	2.0 +/- 0.1
7-8	IS	IS	1.4 +/- 0.1
8-9	IS	IS	0.96 +/- 0.07
9-10	IS	IS	1.19 +/- 0.07
10-12	243 +/- 1	3.01 +/- 0.01	0.96 +/- 0.07
12-14	181 +/- 1	2.24 +/- 0.01	0.56 +/- 0.03
14-16	165 +/- 1	2.04 +/- 0.01	0.56 +/- 0.03
16-18	142 +/- 1	1.76 +/- 0.01	0.32 +/- 0.03
18-20	141 +/- 1	1.74 +/- 0.01	0.26 +/- 0.03
20-25	127 +/- 1	1.57 +/- 0.01	0.22 +/- 0.03

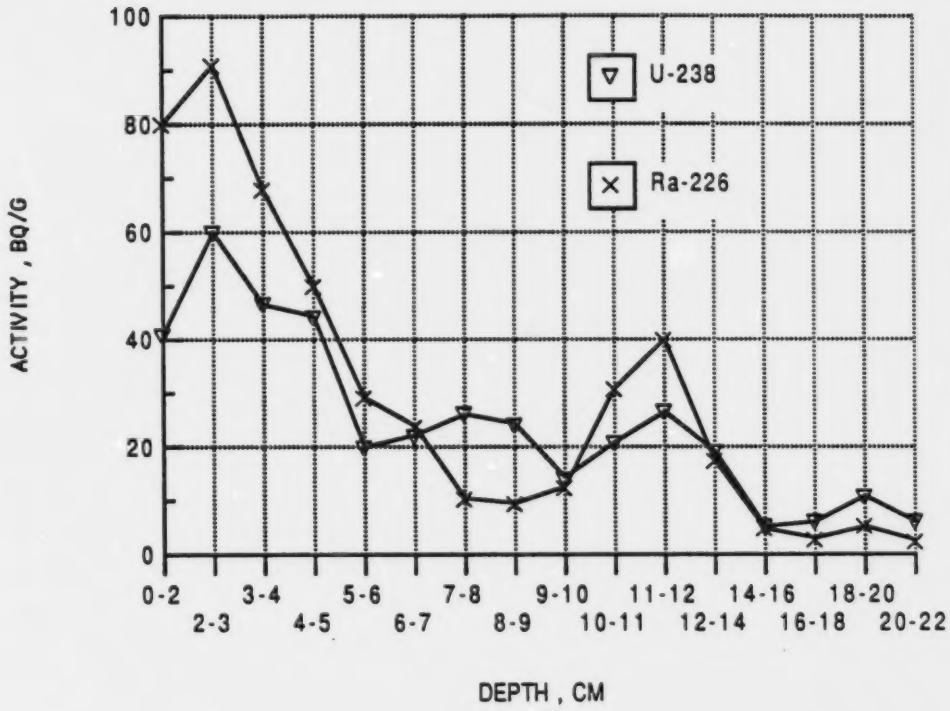
IS = insufficient sample

FIGURE 6

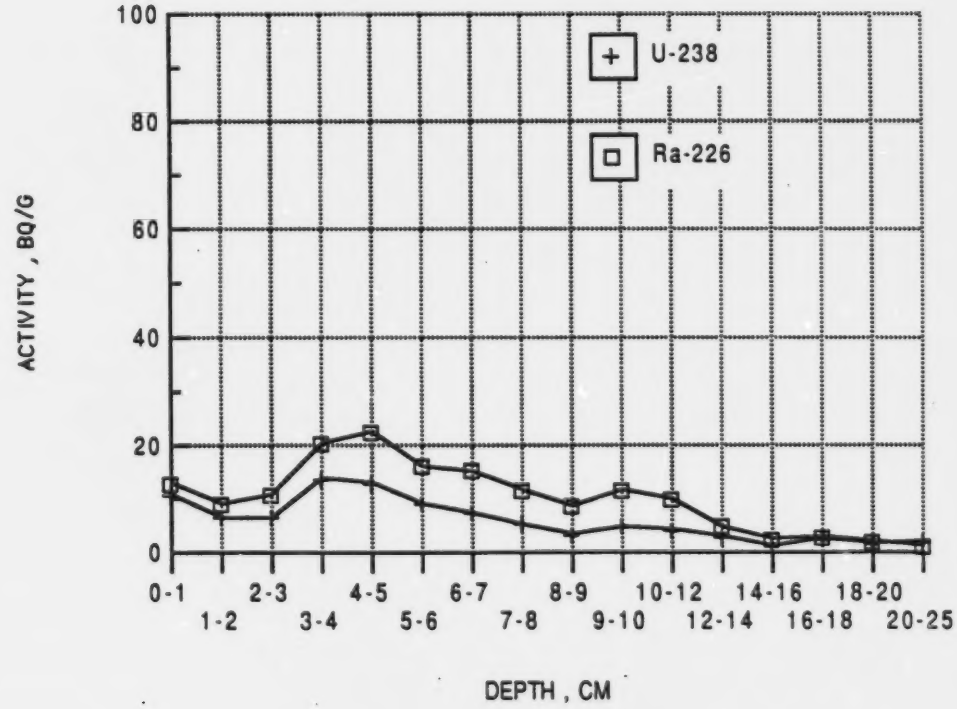
1981 Radionuclide Content of Upper Link Lake Sediment Cores
Plotted as a Function of Sediment Depth
(Taken from Saskmont 1981)

- Upper Link Lake - Core 28A
- Upper Link Lake - Core 29A
- Upper Link Lake - Core 30A
- Upper Link Lake - Core 31A

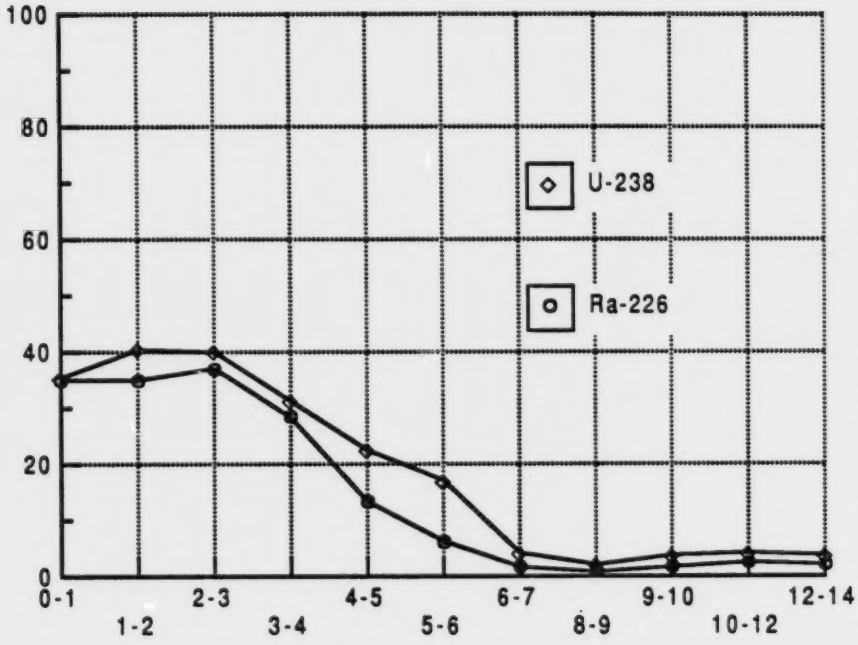
UPPER LINK LAKE-CORE 28A



UPPER LINK LAKE - CORE 29A



UPPER LINK LAKE-CORE 30A



UPPER LINK LAKE-CORE 31A

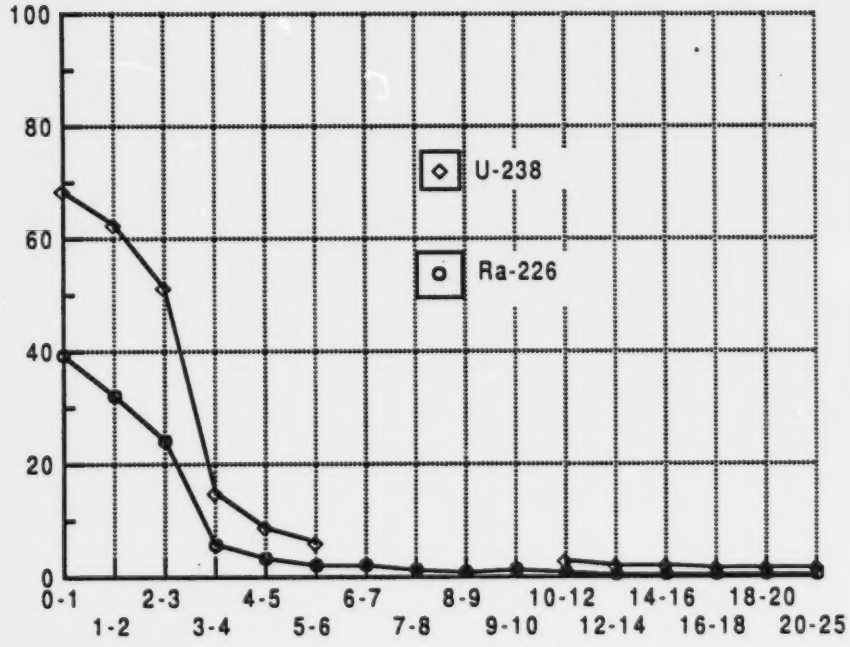
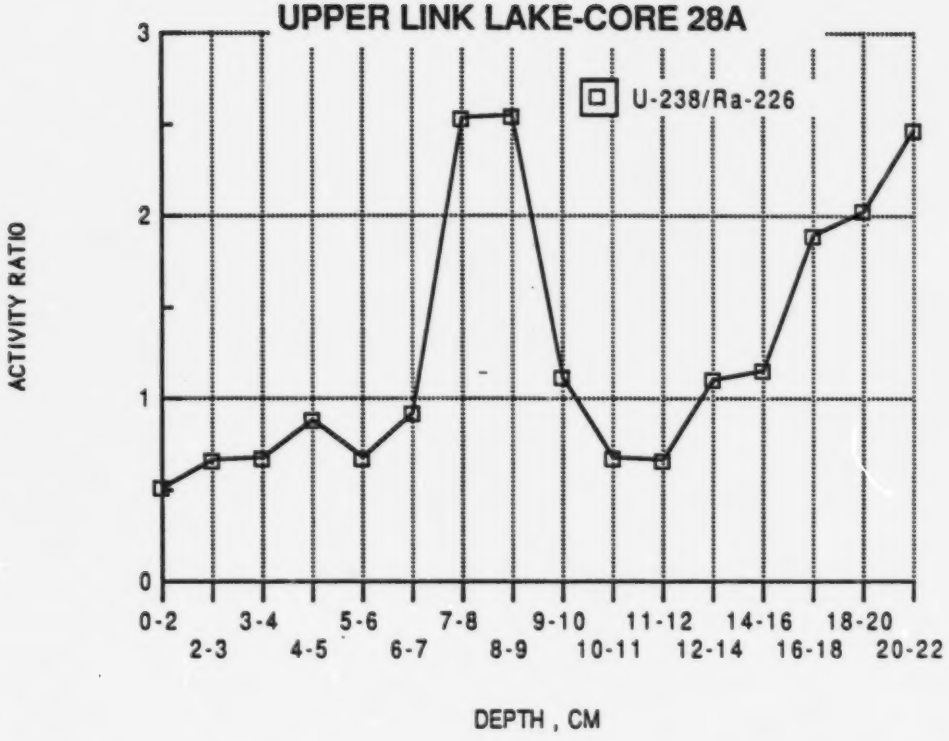
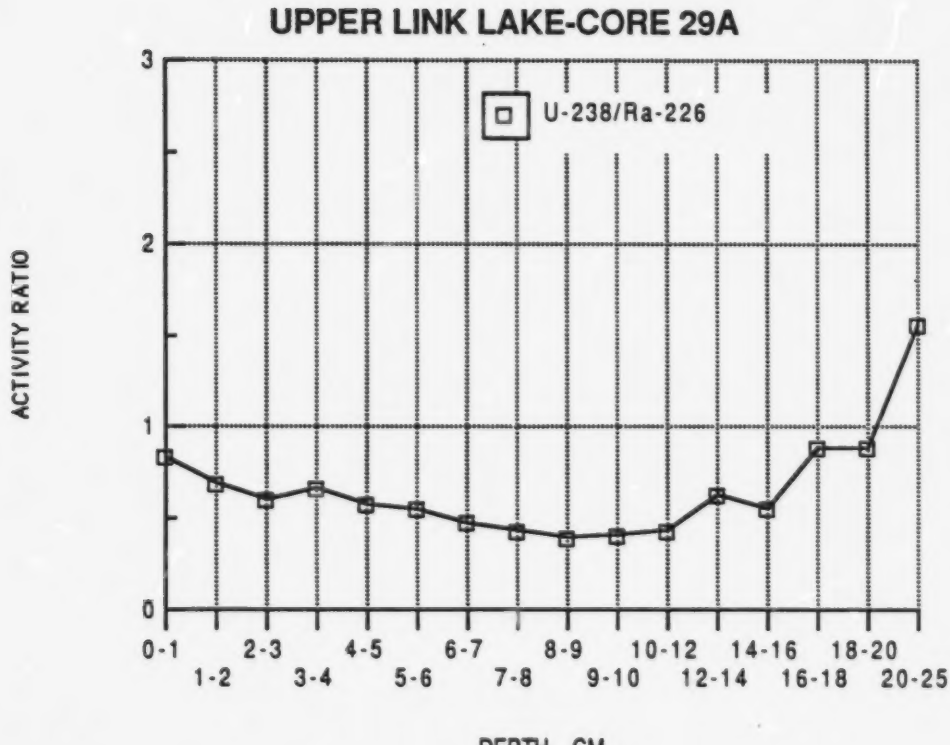


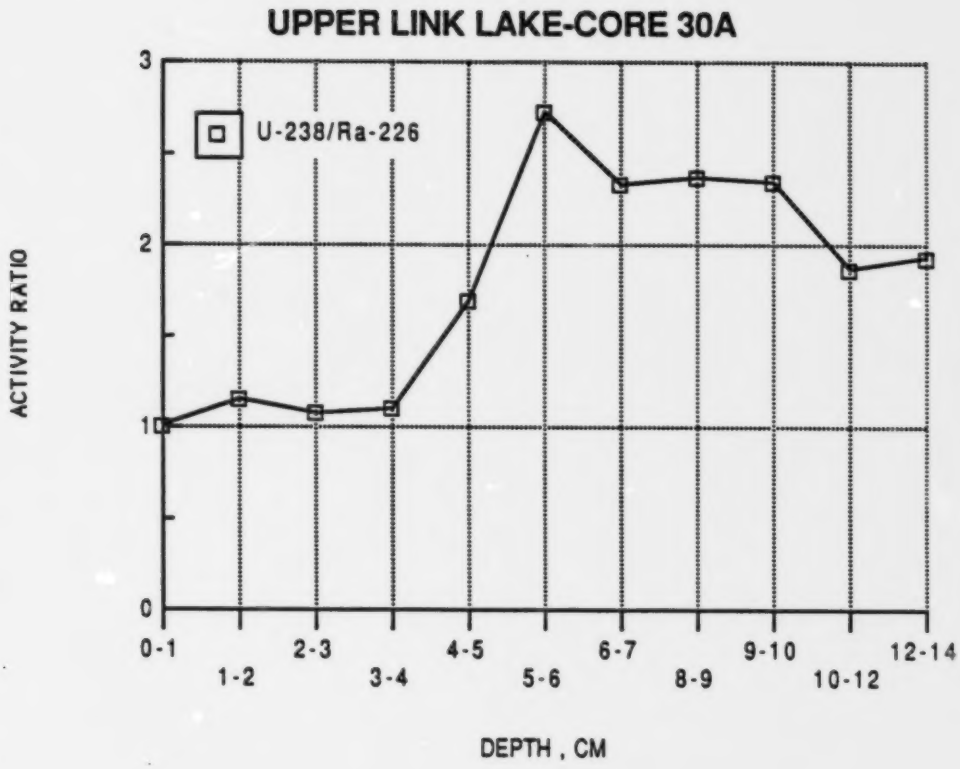
FIGURE 7

Plot of U-238/Ra-226 Activity Ratio as a Function of Depth in
Upper Link Lake Sediments, 1981
(Taken from Saskmont 1981)

- Upper Link Lake - Core 28A
- Upper Link Lake - Core 29A
- Upper Link Lake - Core 30A
- Upper Link Lake - Core 31A


UPPER LINK LAKE-CORE 28A
U-238/Ra-226
ACTIVITY RATIO
3
2
1
0
0-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-14
14-16
16-18
18-20
20-22
DEPTH , CM


UPPER LINK LAKE-CORE 29A
U-238/Ra-226
ACTIVITY RATIO
3
2
1
0
0-1
1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10
10-12
12-14
14-16
16-18
18-20
20-25
DEPTH , CM


UPPER LINK LAKE-CORE 30A
U-238/Ra-226
ACTIVITY RATIO
0
1
2
3
0-1
1-2
2-3
3-4
4-5
5-6
6-7
8-9
9-10
10-12
12-14
DEPTH , CM

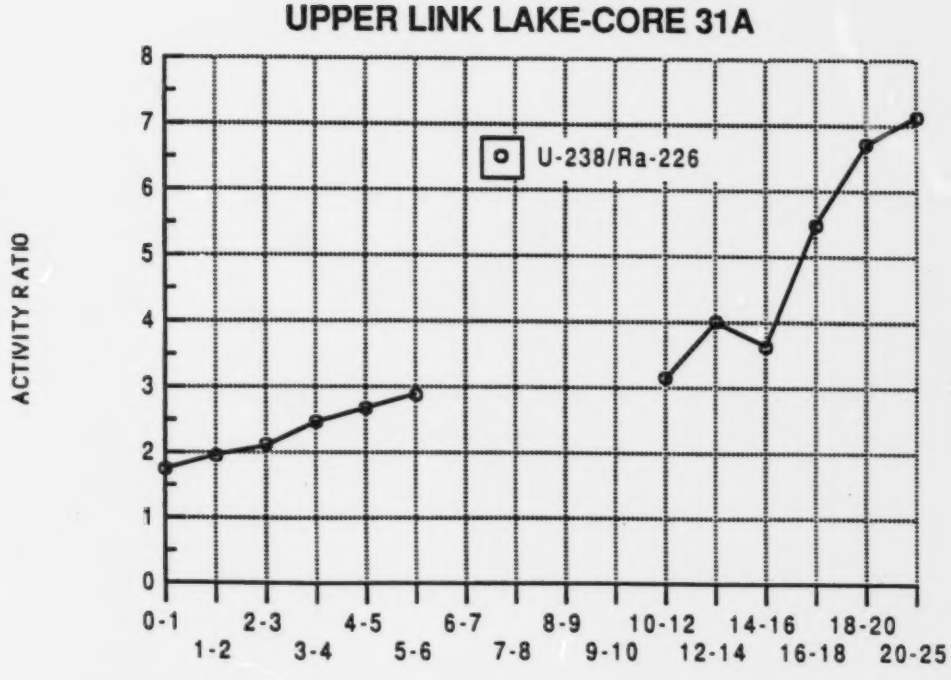
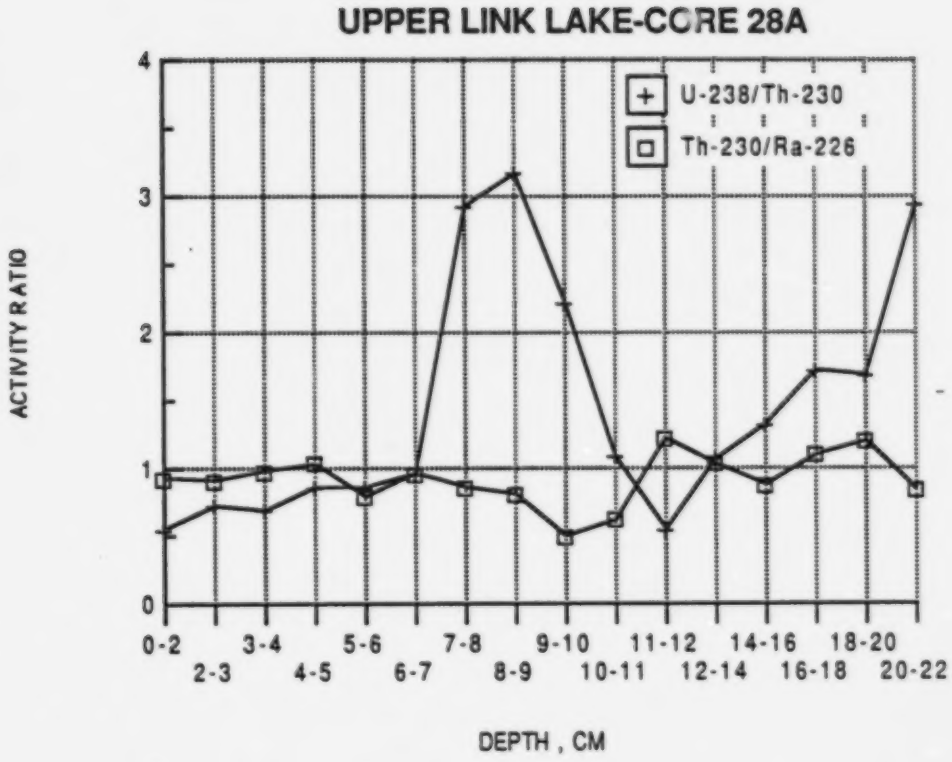

UPPER LINK LAKE-CORE 31A
U-238/Ra-226
ACTIVITY RATIO
0
1
2
3
4
5
6
7
8
0-1
1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10
10-12
12-14
14-16
16-18
18-20
20-25
DEPTH , CM

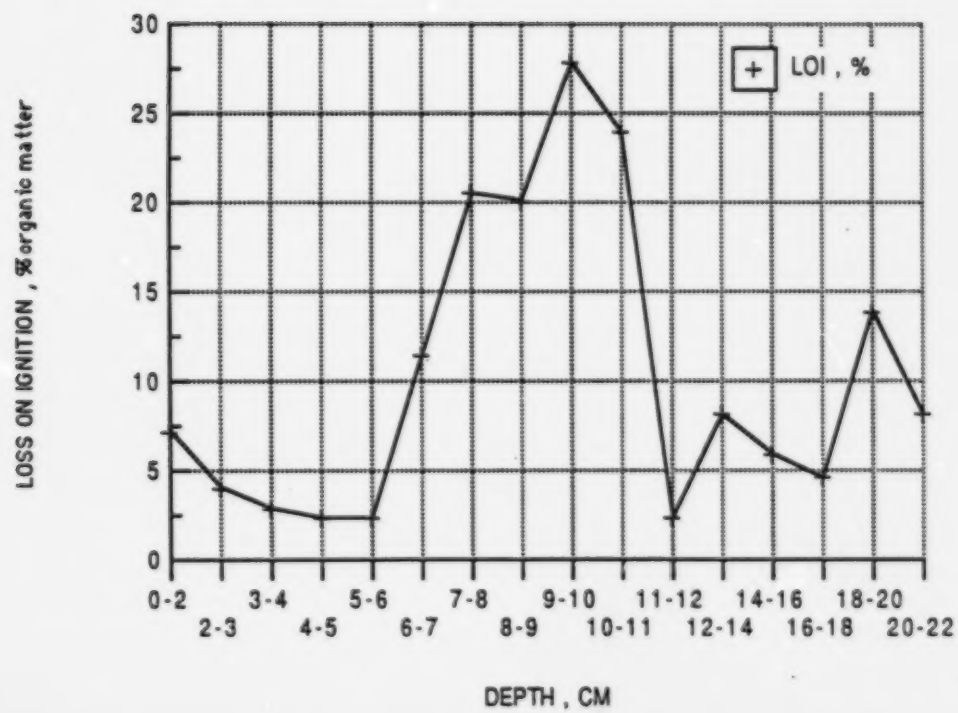
TABLE 10 Detailed radiochemical analysis of Upper Link Lake sediment core 28A.(taken from Saskmont.1980)

DEPTH , CM	U,ug/g	Bq/g (dried weight) U-238 (calculated)	Ra-226	Th-230	LOI , %
LOCATION 28A					
0-2	3320 +/- 10	41.1 +/- 0.1	80 +/- 3	75 +/- 3	7.2 +/- 0.2
2-3	4860 +/- 10	60.1 +/- 0.1	91 +/- 4	83 +/- 3	4.1 +/- 0.2
3-4	3760 +/- 10	46.5 +/- 0.1	68 +/- 3	67 +/- 3	2.9 +/- 0.2
4-5	3600 +/- 10	44.5 +/- 0.1	50 +/- 2	52 +/- 3	2.4 +/- 0.2
5-6	1600 +/- 10	19.8 +/- 0.1	29 +/- 1	23 +/- 1	2.4 +/- 0.2
6-7	1800 +/- 10	22.3 +/- 0.1	24 +/- 1	23 +/- 1	11.4 +/- 0.2
7-8	2110 +/- 10	26.1 +/- 0.1	10.3 +/- 0.4	8.9 +/- 0.4	20.5 +/- 0.2
8-9	1980 +/- 10	24.5 +/- 0.1	9.6 +/- 0.4	7.7 +/- 0.4	20.1 +/- 0.2
9-10	1150 +/- 10	14.2 +/- 0.1	12.7 +/- 0.6	6.4 +/- 0.4	27.9 +/- 0.2
10-11	1690 +/- 10	20.9 +/- 0.1	31 +/- 1	19.1 +/- 0.9	23.9 +/- 0.2
11-12	2160 +/- 10	26.7 +/- 0.1	40 +/- 2	49 +/- 2	2.4 +/- 0.2
12-14	1540 +/- 10	19.1 +/- 0.1	17.2 +/- 0.7	17.8 +/- 0.8	8.2 +/- 0.2
14-16	438 +/- 1	5.41 +/- 0.01	4.7 +/- 0.2	4.1 +/- 0.2	5.9 +/- 0.2
16-18	475 +/- 1	5.88 +/- 0.01	3.1 +/- 0.2	3.4 +/- 0.2	4.6 +/- 0.2
18-20	886 +/- 1	10.96 +/- 0.01	5.4 +/- 0.2	6.5 +/- 0.3	13.9 +/- 0.2
20-22	501 +/- 1	6.20 +/- 0.01	2.5 +/- 0.1	2.1 +/- 0.2	8.2 +/- 0.2

FIGURE 8

Plot of U-238/Th-230 and Th-230/Ra-226 Activity in Upper Link Lake Sediment Core 28A as a Function of Depth


UPPER LINK LAKE-CORE 28A
U-238/Th-230
Th-230/Ra-226
ACTIVITY RATIO
0
1
2
3
4
0-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-14
14-16
16-18
18-20
20-22
DEPTH , CM


LOI , %
LOSS ON IGNITION , % organic matter
0
5
10
15
20
25
30
0-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-14
14-16
16-18
18-20
20-22
DEPTH , CM

Only at a depth of 14 centimeters did the U-238 activity approach the 1972-1974 findings. A knowledge of the Pb-210 and U-234 activity profile may have been helpful in further elucidating the history of this sediment core.

For the purpose of this NUTP project study, core samples were taken from Horseshoe Pond, a body of water whose history had not been severely influenced by the action of man.

It should be understood that most of the historical data discussed in this section, especially that pertaining to Upper Link Lake, reflects the influences of mine slime settling, waste rock erosion and settling and the mine start-up, in general. While it was recognized that the chemistry of these sediments could differ drastically from the chemistry resulting from the natural sedimentation process expected in Horseshoe Pond, it has been included for the following reasons:

(1) Generally speaking, the data base concerning radionuclide contents of fresh water lake sediment is small. The data contained in Garratt's report (1984) represent, not only a significant tabulation of information concerning fresh water lake sediment composition, but also lake sediments taken from the vicinity of Horseshoe Pond. While it is recognized that much of the sediment compositions quoted in this section may reflect the influence of human activity, the knowledge of those influences which accompany the data gives a combination that may be useful for interpreting the data obtained in this (Horseshoe Pond) study and any similar studies that follow.

(2) According to Garratt (1984) Rabbit Lake was dewatered from 1971 to 1974. Cameron's and Sawchyn's data, measured in 1974 and 1972 respectively, although few in number, suggested that Upper Link Lake and Lower Link Lake sediment was not influenced by the dewatering. The conclusion by Garratt (1984) that the relatively high uranium levels in Upper Link Lake sediment arrived via the mechanism - oxidation of the Rabbit Lake deposit, followed by ground water

hydromorphic transport - is considered of possible significance to interpreting the data obtained in this (Horseshoe Pond) study and subsequent studies.

(3) The influence of Rabbit Lake mining on Upper Link Lake sediment (Saskmont.1980) is relevant to this report only in that it confirms that Rabbit Lake sediments were transported to Upper Link Lake. The depth profiles that resulted are of limited relevance to this report. However, when those data are considered, in conjunction with the data from sediment cores taken from Upper Link Lake in 1981, the influence of one year of mining and milling operation is noted. This influence may be of assistance with interpreting the data obtained in this (Horseshoe Pond) study and other subsequent studies.

(4) The sediment data pertaining to Horseshoe Pond, Hidden Bay and Pow Bay contained in the 1980 Saskmont report are significant in that they tend to confirm earlier levels reported by Knight (1971) and Cameron (1977). Although limited in quantity, these data provide some idea of historical background levels in those locations. They also confirm that significant environmental changes had not taken place in Horseshoe Pond sediments between 1971 and 1980; a fact considered relevant to interpreting the data contained in this (Horseshoe Pond) study.

(5) Reference to Marie and Fookes Lake sediments confirms the distribution of U, Ra-226, Th-230 and Pb-210 activities that would be expected when mill tailings or eroded ore particles find their way into lake sediments. This is considered relevant to interpreting the data contained in this (Horseshoe Pond) study.

The results of the Horseshoe Pond study and interpretation of these results follow.

III. RESULTS AND DISCUSSIONS

As described earlier, sediment cores were taken at four locations in Horseshoe Pond (see Figure 3). Core HL-1 was taken near the inflow (from the mining operation) to the pond and Core HL-4 which was taken near the outflow (to Hidden Bay) from the pond. The two other sediment cores were taken at intermediate locations and a fifth sediment core (HBE-1) was taken at Hidden Bay near the effluent from Horseshoe Pond. Surface water samples were taken at locations HL-1 and HL-4. All sediment cores were sectioned in the field, placed in plastic bags, refrigerated and returned to the laboratory. There, the interstitial water was removed from the Horseshoe Pond segments by the application of high pressure (80 psi). The resulting cores were dried, crushed and stored in plastic containers while awaiting analysis. The interstitial and surface water samples were analyzed immediately for major cations, anions and naturally occurring radionuclides. For interstitial water samples, where the volume obtained was too little for complete analysis, it was necessary to carry out appropriate dilutions with de-ionized water. As a consequence, the analysis detection limits reported for the analyses of the interstitial waters were poorer than were reported for the surface water analyses. The results of the surface water analyses are shown in Table 11.

3.1 Interstitial Water Analysis

The study of the composition of the interstitial solutions in sediments can provide an understanding of the principles governing diagenesis of clay minerals. In the Horseshoe Pond sediments, it was speculated that a knowledge of where the ions were would give some insight into mechanisms of change within the sediments. The ions contained in the water solutions removed from sediments can originate from three main locations:

1) the interstitial solution which includes soluble species;
2) the exchangeable sites on the sediment; and

TABLE 11

Water Quality Analysis for Horseshoe Pond

		Sample Location	
		HL-1 (Near Inlet)	HL-4 (Near Outlet)
pH		5.27 ± 0.02	6.09 ± 0.02
SO_4,	mg/L	3830 ± 10	2530 ± 10
Cl,	mg/L	74 ± 1	51 ± 1
Ba,	mg/L	0.03 ± 0.01	0.03 ± 0.01
Ca,	mg/L	210 ± 5	140 ± 5
Fe,	mg/L	0.59 ± 0.02	0.47 ± 0.02
K,	mg/L	<1	<1
Mg,	mg/L	730 ± 10	500 ± 10
Mn,	mg/L	2.1 ± 0.1	1.4 ± 0.1
Na,	mg/L	51 ± 1	37 ± 1
Alkalinity-P,	mg/L $CaCO_3$	0	0
Alkalinity-T,	mg/L $CaCO_3$	9 ± 1	14 ± 1
TSS,	mg/L	6.2 ± 0.2	2.8 ± 0.2
TDS,	mg/L	6750 ± 10	4470 ± 10
U,	ug/L	86 ± 2	50 ± 2
Ra-226,	Bq/L	≤0.01	≤0.01
Th-230,	Bq/L	0.22 ± 0.03	0.03 ± 0.01
Pb-210,	Bq/L	≤0.5	≤0.5

TABLE 12 Data from the analysis of interstitial water removed from sediment cores taken at Horseshoe Pond

INTERSTICIAL SAMPLE NO.	DEPTH,CM.	pH +/- 0.02	SO4 +/- 0.2	Cl +/- 0.1	Ba +/-0.0003	Ca +/- 0.3	Fe +/- 0.001	
				milliequivalents/Litre				
HL1-1	0-2	6.14	77.8	2.2	0.0009	11.0	0.034	<
-2	2-5	6.31	90.0	2.5	0.0007	12.0	0.031	<
-3	5-10	6.07	90.8	2.9	0.0009	14.0	0.069	<
-4	10-15	7.08	96.4	3.1	0.0010	15.5	0.020	<
-5	15-20	6.81	97.1	3.2	0.0007	16.0	0.007	<
-6	20-25	5.85	94.9	3.4	0.0015	16.5	0.100	<
-7	25-30	7.40	94.1	3.0	0.0010	15.5	0.014	<
-8	30-35	6.60	58.5	2.8	0.0009	11.5	< 0.007	<
-9	35-40	IS	IS	IS	IS	IS	IS	
HL2-1	0-2	6.53	67.9	1.7	0.0009	10.0	0.014	<
-2	2-5	6.44	75.8	1.7	0.0013	11.0	0.028	<
-3	5-10	6.94	78.8	2.0	0.0007	11.0	< 0.005	<
-4	10-15	6.87	39.2	1.6	0.0007	7.0	< 0.007	<
-5	15-20	7.08	18.6	3.9	0.0007	4.3	< 0.008	<
-6	20-25	7.30	10.1	2.2	0.0010	3.7	< 0.009	<
-7	25-30	6.82	5.0	0.7	0.0007	1.6	< 0.009	<
-8	30-35	6.90	2.7	0.5	0.0010	2.0	0.010	<
-9	35-40	IS	IS	IS	IS	IS	IS	
HL3-1	0-2	6.40	61.5	1.6	0.0007	10.0	0.022	<
-2	2-5	6.00	83.6	2.1	0.0006	12.0	0.052	<
-3	5-10	6.63	109.7	2.8	0.0007	14.5	0.007	<
-4	10-15	6.96	122.1	3.7	0.0007	17.5	0.016	<
-5	15-20	6.26	147.0	4.6	0.0009	20.5	0.011	<
-6	20-25	7.16	86.6	4.1	0.0007	17.0	< 0.004	<
-7	25-30	7.34	63.2	3.9	0.0009	16.0	0.008	<
-8	30-35	5.16	50.6	3.5	0.0009	14.0	0.076	<
-9	35-40	6.22	36.8	3.1	0.0007	11.0	0.045	
HL4-1	0-2	6.37	71.2	1.9	0.0006	10.0	0.007	<
-2	2-5	6.80	90.0	2.3	0.0006	12.5	0.004	<
-3	5-10	6.93	98.6	2.7	0.0007	15.0	0.003	<
-4	10-15	6.82	102.4	3.1	0.0006	17.0	0.034	<
-5	15-20	6.89	64.7	2.6	0.0006	11.0	< 0.004	<
-6	20-25	7.40	38.1	2.4	0.0006	8.5	0.012	<
-7	25-30	IS	IS	IS	IS	IS	IS	
-8	30-35	6.68	34.5	2.9	0.0010	10.0	0.022	<
-9	35-40	IS	IS	IS	IS	IS	IS	
-10	40-45	IS	IS	IS	IS	IS	IS	

*IS=INSUFFICIENT SAMPLE

** = RATIO MILLIEQUIVALENTS ANIONS/LITRE TO MILLIEQ

emoved from sediment cores taken at Horseshoe Pond

milliequivalents/Litre								anions** / cations	water sediment
Cl	Ba	Ca	Fe	K	Mg	Mn	Na		
0.1	+/-0.0003	+/- 0.3	+/- 0.001		+/- 0.8	+/- 0.01	+/- 0.04	+/- 0.1	gm/gm
2.2	0.0009	11.0	0.034	< 0.07	65.6	0.09	2.26	1.01	2.02
2.5	0.0007	12.0	0.031	< 0.06	70.8	0.08	2.48	1.08	0.99
2.9	0.0009	14.0	0.069	< 0.07	66.5	0.11	2.83	1.12	0.27
3.1	0.0010	15.5	0.020	< 0.05	75.2	0.11	2.91	1.06	0.23
3.2	0.0007	16.0	0.007	< 0.07	77.0	0.11	2.70	1.05	0.11
3.4	0.0015	16.5	0.100	< 0.06	67.3	0.13	3.17	1.13	0.19
3.0	0.0010	15.5	0.014	< 0.11	74.3	0.07	2.74	1.05	0.11
2.8	0.0009	11.5	< 0.007	< 0.12	43.8	0.08	2.35	1.06	0.1
IS	IS	IS	IS	IS	IS	IS	IS	IS	IS
1.7	0.0009	10.0	0.014	< 0.06	61.2	0.07	1.65	0.95	4.87
1.7	0.0013	11.0	0.028	< 0.06	64.8	0.07	1.74	1.00	2.11
2.0	0.0007	11.0	< 0.005	< 0.10	63.0	0.05	1.87	1.06	0.46
1.6	0.0007	7.0	< 0.007	< 0.13	28.0	0.04	1.43	1.11	0.24
3.9	0.0007	4.3	< 0.008	< 0.14	11.4	0.03	0.87	1.34	0.22
2.2	0.0010	3.7	< 0.009	< 0.17	6.6	0.01	0.61	1.12	0.15
0.7	0.0007	1.6	< 0.009	< 0.14	2.2	0.01	0.31	1.30	0.21
0.5	0.0010	2.0	0.010	< 0.18	1.0	0.00	0.16	0.96	0.11
IS	IS	IS	IS	IS	IS	IS	IS	IS	IS
1.6	0.0007	10.0	0.022	< 0.03	58.6	0.08	1.74	0.90	7.33
2.1	0.0006	12.0	0.052	< 0.03	73.5	0.07	2.04	0.98	3.74
2.8	0.0007	14.5	0.007	< 0.03	87.5	0.09	2.52	1.07	3.15
3.7	0.0007	17.5	0.016	< 0.04	105.0	0.12	3.43	1.00	1.48
4.6	0.0009	20.5	0.011	< 0.05	122.5	0.14	4.04	1.03	0.93
4.1	0.0007	17.0	< 0.004	< 0.07	55.2	0.22	3.35	1.20	0.62
3.9	0.0009	16.0	0.008	< 0.10	35.8	0.26	3.09	1.21	0.34
3.5	0.0009	14.0	0.076	< 0.13	25.3	0.28	2.48	1.28	0.24
3.1	0.0007	11.0	0.045	0.12	15.8	0.24	2.04	1.37	0.22
1.9	0.0006	10.0	0.007	< 0.04	59.5	0.07	1.57	1.03	4.22
2.3	0.0006	12.5	0.004	< 0.05	74.3	0.07	2.04	1.04	2.06
2.7	0.0007	15.0	0.003	< 0.06	82.2	0.11	2.70	1.01	1.45
3.1	0.0006	17.0	0.034	< 0.04	86.6	0.13	3.00	0.99	1.32
2.6	0.0006	11.0	< 0.004	< 0.07	54.2	0.09	2.57	0.99	0.58
2.4	0.0006	8.5	0.012	< 0.09	27.1	0.09	2.13	1.07	0.4
IS	IS	IS	IS	IS	IS	IS	IS	IS	IS
2.9	0.0010	10.0	0.022	< 0.18	21.9	0.17	2.04	1.09	0.13
IS	IS	IS	IS	IS	IS	IS	IS	IS	IS
IS	IS	IS	IS	IS	IS	IS	IS	IS	IS

*IS=INSUFFICIENT SAMPLE

** = RATIO MILLIEQUIVALENTS ANIONS/LITRE TO MILLIEQUIVALENTS CATIONS/LITRE

TABLE 13- Radiochemical Data from the analysis of interstitial water removed from sediment cores taken at Horseshoe Pond.

INTERSTICIAL SAMPLE NO.	DEPTH,CM.	U , ug/L	Bq/L Ra-226	Th-230	Pb-210
HL1-1	0-2	37.8 +/-0.2	<0.3	<0.3	< 10
-2	2-5	42.7 +/-0.2	<0.2	<0.2	< 10
-3	5-10	11.6 +/-0.2	0.59+/-0.14	<0.3	< 10
-4	10-15	12.2 +/-0.2	<0.2	<0.2	< 10
-5	15-20	17.2 +/-0.2	<0.3	<0.3	< 10
-6	20-25	2.6 +/-0.2	<0.3	<0.3	< 10
-7	25-30	7.8 +/-0.2	<0.4	<0.4	< 10
-8	30-35	<2	<0.5	<0.5	< 10
-9	35-40	IS	IS	IS	IS
HL2-1	0-2	84 +/-2	<0.2	<0.2	< 10
-2	2-5	9.6 +/-0.2	<0.2	<0.2	< 10
-3	5-10	6.9 +/-0.2	0.5+/-0.3	<0.4	< 10
-4	10-15	16.1 +/-0.2	<0.5	<0.5	< 10
-5	15-20	4.3 +/-0.2	<0.5	<0.5	< 10
-6	20-25	16.2 +/-0.2	<0.7	<0.7	< 10
-7	25-30	4.3 +/-0.2	<0.5	<0.5	< 10
-8	30-35	19.9 +/-0.2	<0.7	<0.7	< 10
-9	35-40	IS	IS	IS	IS
HL3-1	0-2	51 +/-2	<0.1	<0.1	< 10
-2	2-5	71 +/-2	<0.1	<0.1	< 10
-3	5-10	12.1 +/-0.2	<0.2	<0.2	< 10
-4	10-15	23.7 +/-0.2	<0.2	<0.2	< 10
-5	15-20	12.2 +/-0.2	<0.2	<0.2	< 10
-6	20-25	10.6 +/-0.2	<0.3	<0.3	< 10
-7	25-30	15.1 +/-0.2	<0.4	<0.4	< 10
-8	30-35	135 +/-5	<0.5	<0.5	< 10
-9	35-40	4.5 +/-0.2	<0.5	<0.5	< 10
HL4-1	0-2	34.1 +/-0.2	<0.2	<0.2	< 10
-2	2-5	32.8 +/-0.2	<0.2	<0.2	< 10
-3	5-10	17.9 +/-0.2	<0.2	<0.2	< 10
-4	10-15	27.4 +/-0.2	<0.2	<0.2	< 10
-5	15-20	7.1 +/-0.2	<0.3	<0.3	< 10
-6	20-25	10.8 +/-0.2	<0.3	<0.3	< 10
-7	25-30	IS	IS	IS	IS
-8	30-35	18.5 +/-0.2	<0.7	<0.7	< 10
-9	35-40	IS	IS	IS	IS
-10	40-45	IS	IS	IS	IS

* IS = INSUFFICIENT SAMPLE

3) as ions, fixed in structural positions.

Under the terms of this study, only the interstitial solution was examined.

Tables 12 and 13 show the results of the analysis of the interstitial waters removed from the sediment core sections. Table 12 includes the major cation and anion concentrations expressed in units of milliequivalents per liter (me/L). The original analysis data expressed as milligrams per litre (mg/L) is included in the Appendix. The activities of radium-226, thorium-230 and lead-210, expressed in units of bequerels per litre (Bq/L), are shown in Table 13.

Several features concerning the characteristics of the surface and interstitial waters are apparent:

1) The concentrations of the anions and cations contained in the surface water sampled at the outflow of Horseshoe Pond are approximately 68% of the concentrations contained in the surface water sampled at the inflow to Horseshoe Pond. This observation possible reflects the dilution by surface water runoff into Horseshoe Pond.

2) The weight of water recovered from each sediment section, expressed as a function of dry sediment weight, was measured and included in Table 12. Figure 9 illustrates these data graphically and shows a decrease with depth. This trend probably reflects the influence of water pressure on the sediment compaction profile. The variation of this profile for each sediment core would not be unexpected because their origin in the pond was different (see Figure 3). Factors such as surface water depth, organic carbon content and sediment settling characteristics would be expected to influence these profiles.

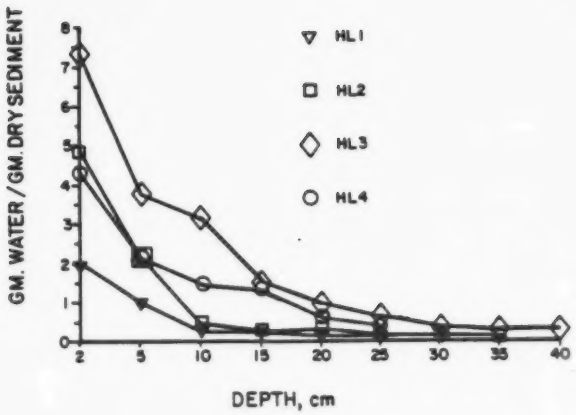


FIGURE 9

PLOT OF WATER CONTENT OF HORSESHOE POND SEDIMENT CORES AS A FUNCTION OF DEPTH

3) The very good ion balances (not including HCO_3/CO_3 contribution) reported in Table 12 indicates that more than 90% of the major cations and anions present in the interstitial waters were accounted for. The concentrations of HCO_3/CO_3 in the interstitial waters was not measured because of the possibility of CO_2 degassing during the extraction process.

4) Figure 10A to G is a plot of the major ion concentrations in the interstitial waters as a function of sediment depth. The precisions of the determinations are reported in Tables 12 and 13 and are reflected, to some degree, by the size of the points in these figures. The figures illustrate that a simple and consistent relationship between the interstitial water composition and depth does not exist. The interstitial waters generally increase in ionic concentration to a depth of between 10 and 20 centimeters and then decrease as the depth increases. The gradients differ inconsistently between each location.

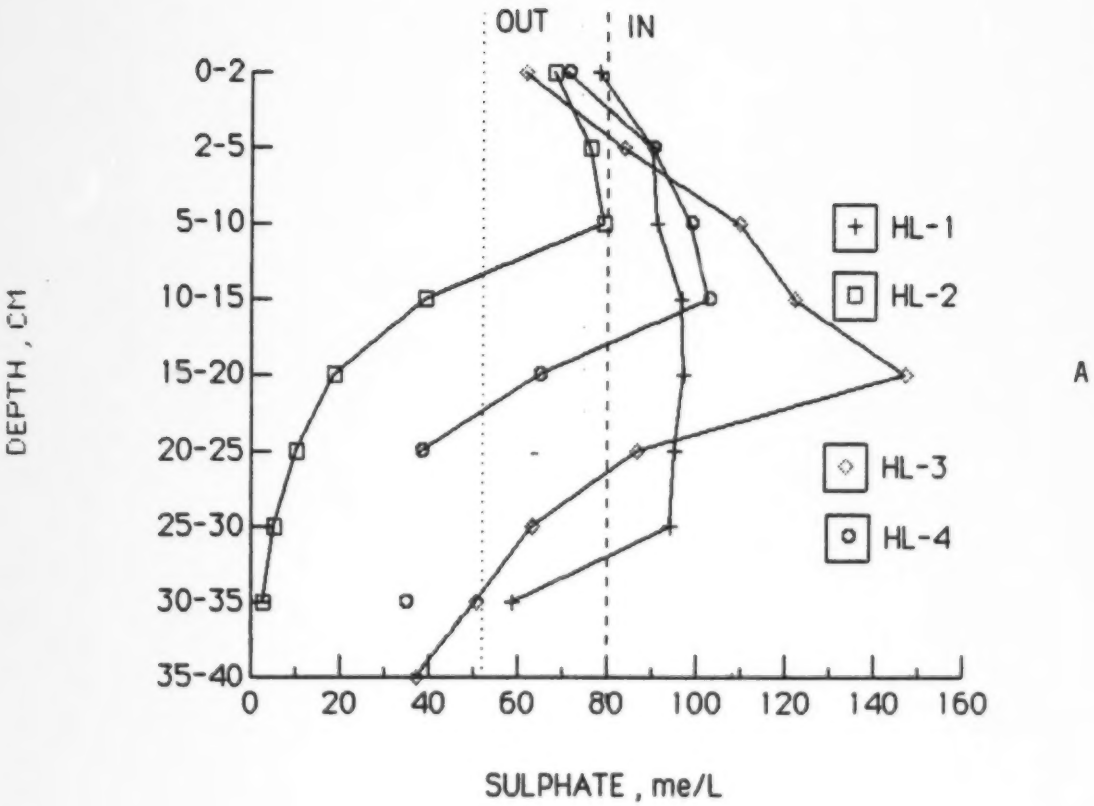
5) The concentrations of the surface waters are also indicated in Figure 10A to G. Except for uranium, the concentrations of the ionic species present in the upper layers (first two centimeters) of the interstitial waters are of the same magnitude as the ionic concentrations noted in the surface water sample taken from the inflow end (Station HL-1) of Horseshoe Pond. The significance of this observation may be clearer if a knowledge of ionic concentration gradients existing in the overlying Horseshoe Pond water, as a function of depth at the time of sampling, was available.

6) The concentration of uranium dissolved in the first two centimeters of the four sediment cores varied from a high of 84 ug/L in HL-2 to a low of 34 ug/L in HL-4. These concentrations resemble the concentrations of uranium in the overlying surface water. For example, the pond water near HL-1 contained 86 ug/L while near HL-4, it contained 50 ug/L. This differs from the concentration profiles

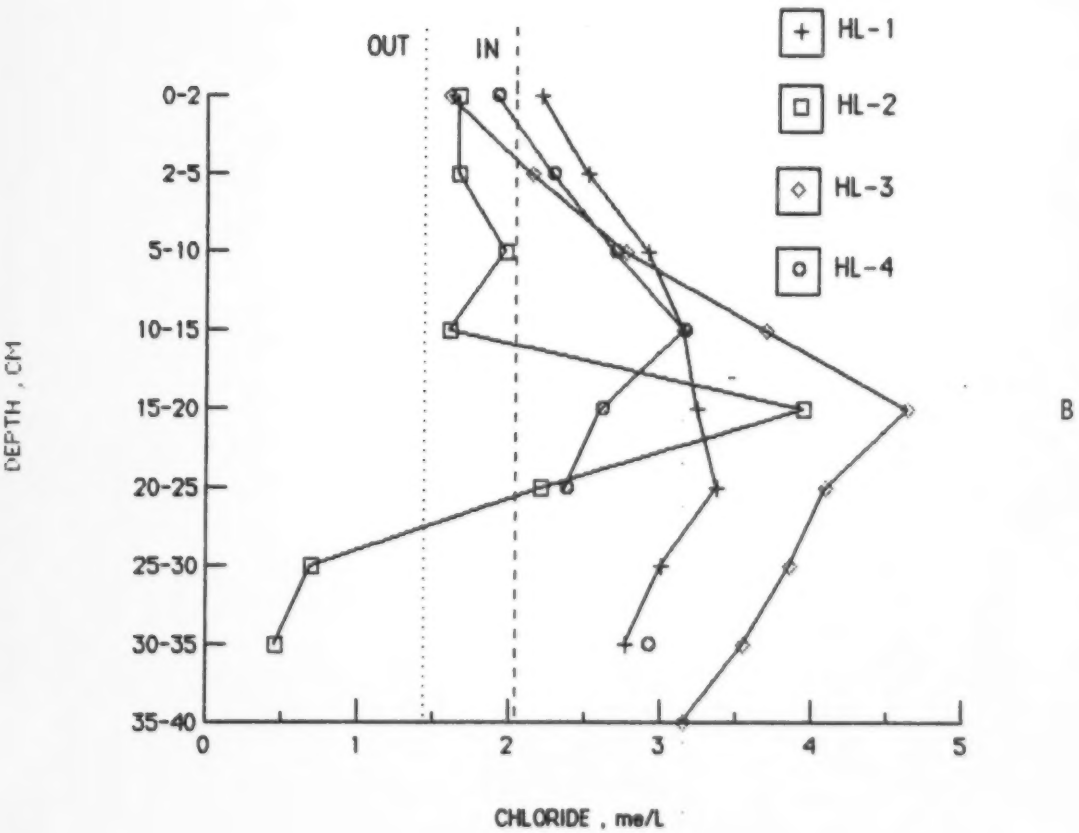
FIGURE 10

PLOT OF ION CONCENTRATIONS IN INTERSTITIAL WATERS OF HORSESHOE POND SEDIMENT CORES AS A FUNCTION OF DEPTH

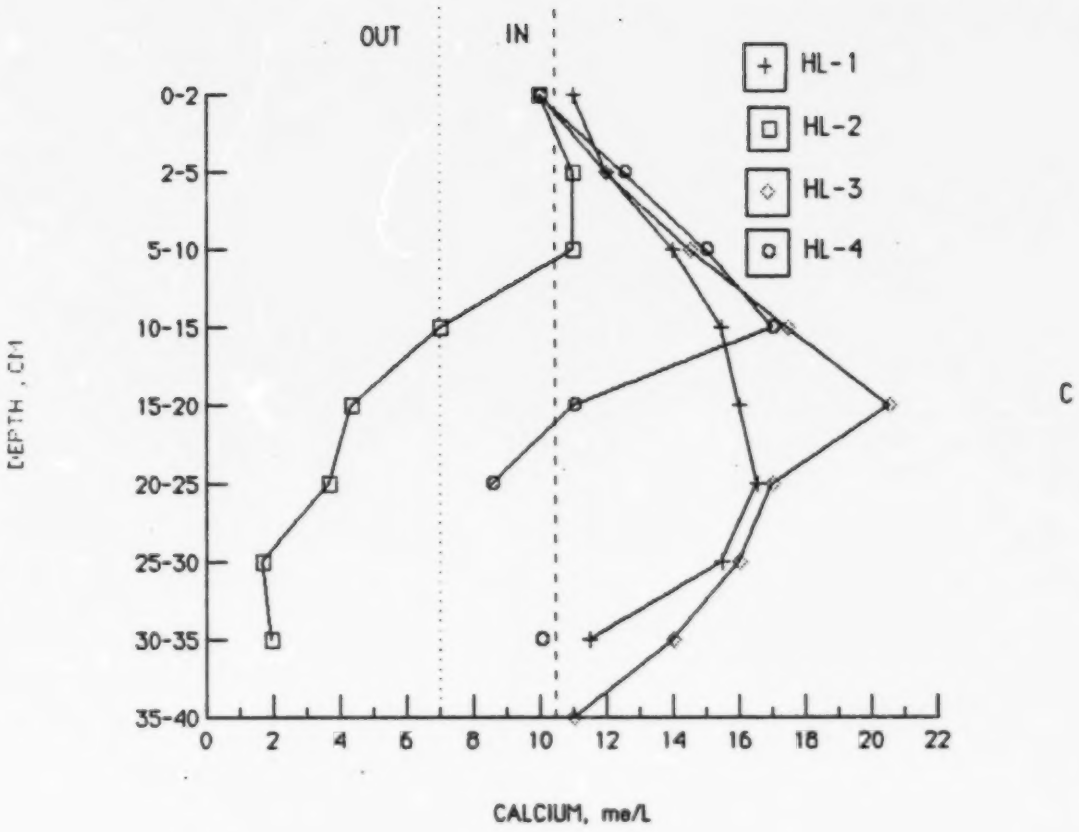
A, Sulphate; B, Chloride; C, Calcium; D, Manganese; E, Magnesium; F, Sodium; G, Uranium. The ionic concentrations of each ionic species measured in the surface water at the inlet and outlet locations of Horseshoe Pond are included in each.


OUT
IN
0-2
2-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
0
20
40
60
80
100
120
140
160
HL-1
HL-2
HL-3
HL-4
DEPTH , CM
SULPHATE , me/L

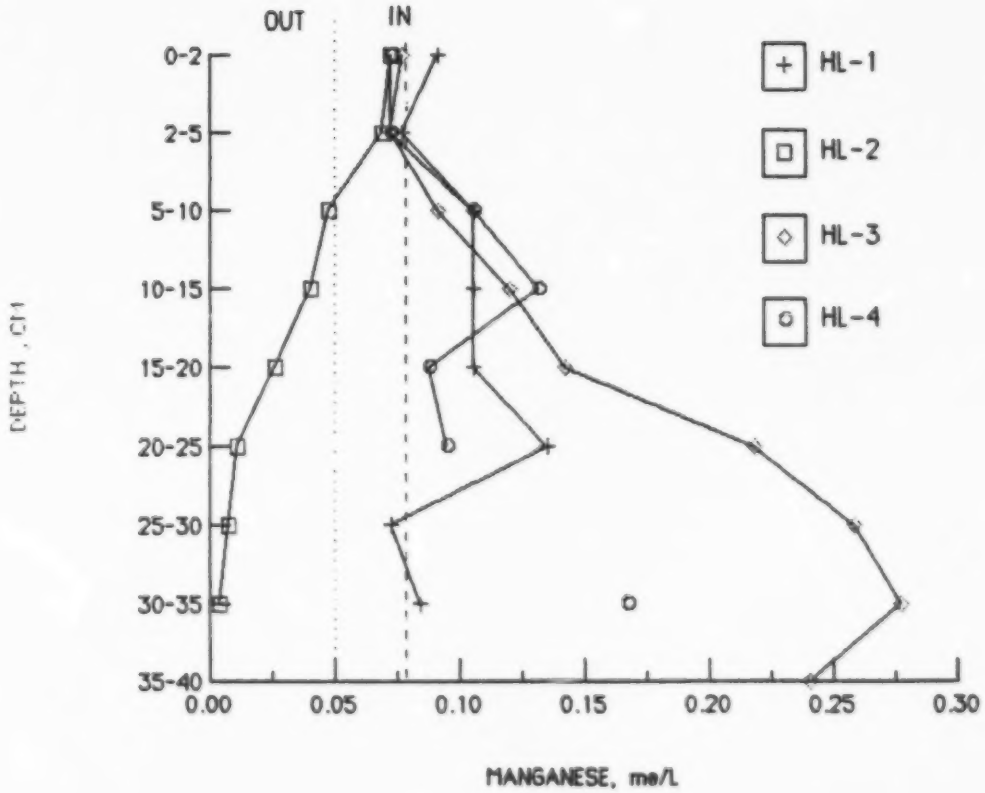
A


OUT
IN
0-2
2-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
0
1
2
3
4
5
HL-1
HL-2
HL-3
HL-4
DEPTH , CM
CHLORIDE , me/L

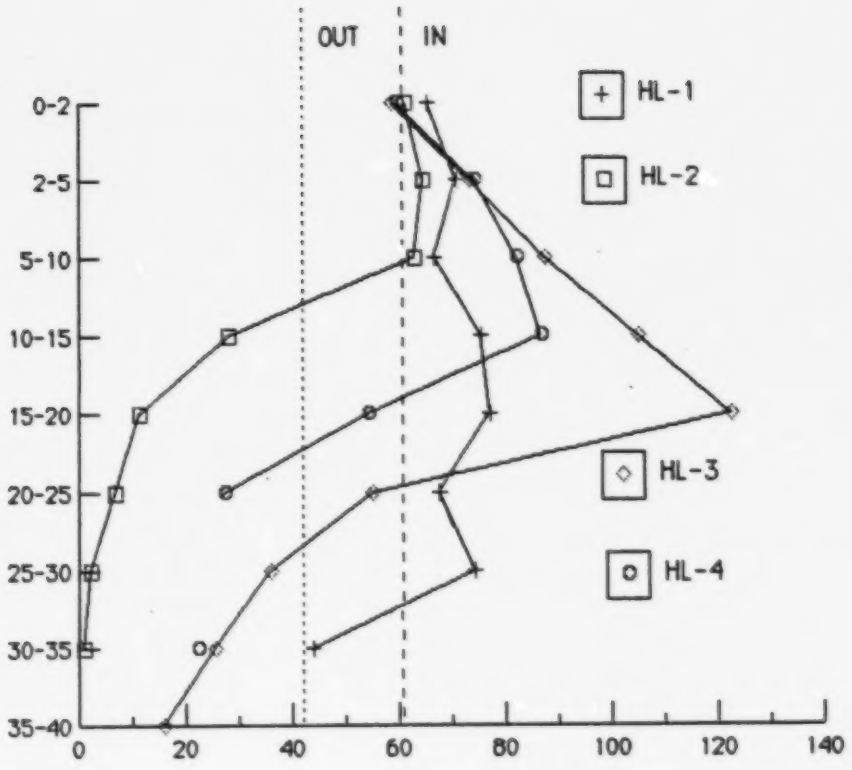
B


OUT
IN
HL-1
HL-2
HL-3
HL-4
0-2
2-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
0
2
4
6
8
10
12
14
16
18
20
22
DEPTH, CM
CALCIUM, me/L

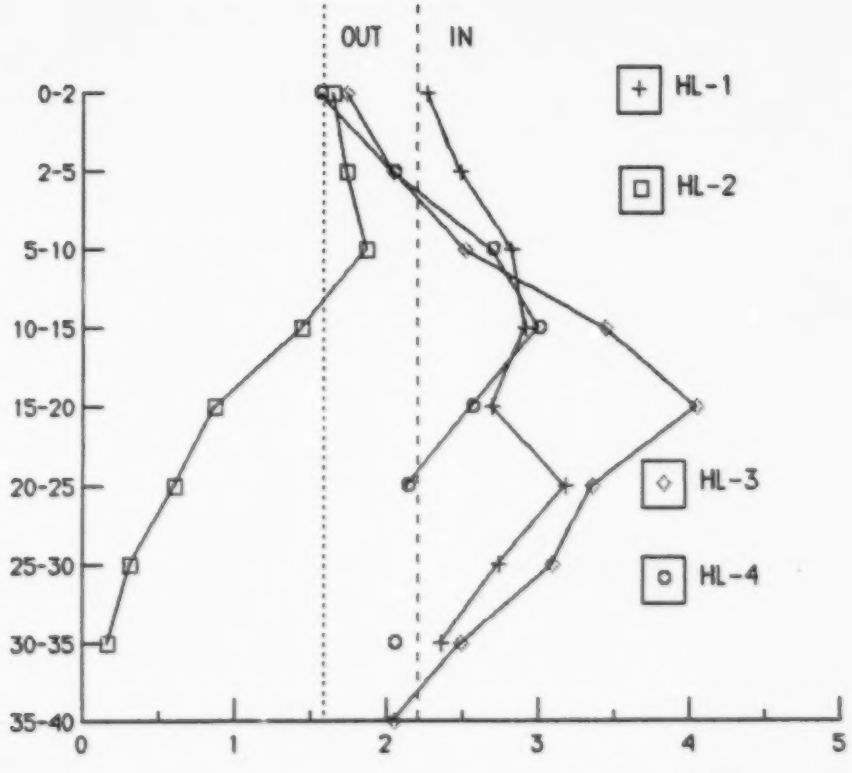
C


OUT
IN
HL-1
HL-2
HL-3
HL-4
0-2
2-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
0.00
0.05
0.10
0.15
0.20
0.25
0.30
DEPTH, CM
MANGANESE, me/L

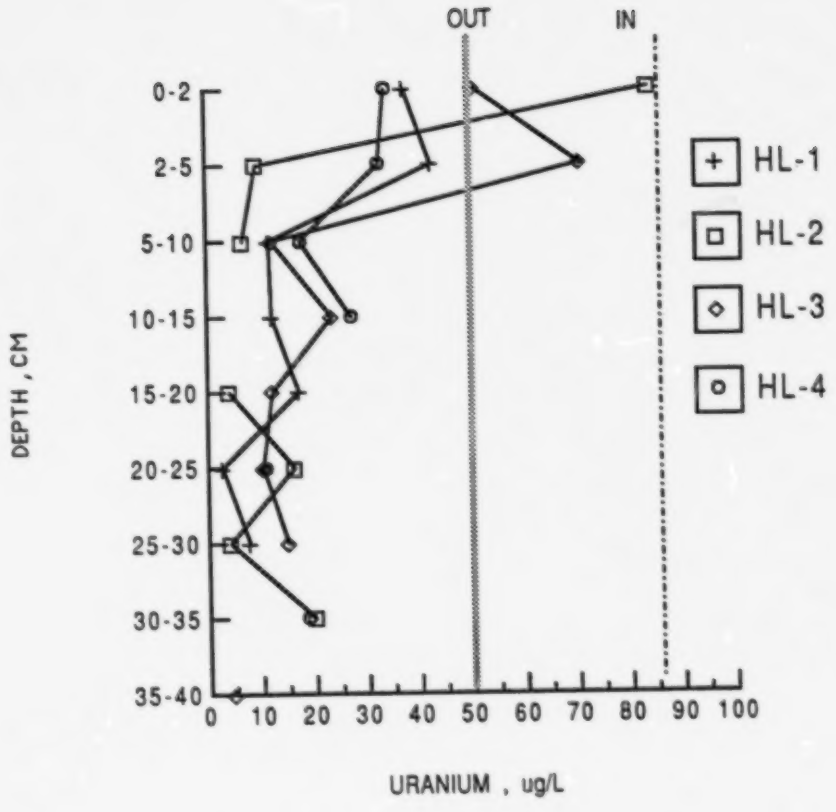
D


OUT
IN
HL-1
HL-2
HL-3
HL-4
0-2
2-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
0
20
40
60
80
100
120
140
DEPTH, CM
MAGNESIUM, me/L

E


OUT
IN
HL-1
HL-2
HL-3
HL-4
0-2
2-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
0
1
2
3
4
5
DEPTH, CM
SODIUM, me/L

F


OUT
IN
0-2
2-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
DEPTH , CM
0 10 20 30 40 50 60 70 80 90 100
URANIUM , ug/L
HL-1
HL-2
HL-3
HL-4

G

of the major cations and anions whose concentrations at the sediment surface closely resembled the concentration in the surface water at the pond inflow.

7) The activities of radium-226, thorium-230 and lead-210 (reported in Table 13) found in the interstitial waters were generally lower than the detection limit of the measurement. This was a result of the small volume of interstitial water available for the radiochemical analyses. This situation could, perhaps, have been avoided by anticipating the low activities in advance and by ensuring that larger volumes of interstitial water were available, through sampling larger volumes of sediment cores. Under the terms of this contract such low activities were not anticipated.

8) A plot of the total cations contained in the interstitial waters of the Horseshoe Pond sediment as a function of depth is shown in Figure 11 while Figure 12 shows the pH variation with depth.

The composition of the interstitial water can be an indicator of lake water/ground water interaction. Its composition may be significantly influenced by the sediment composition. Several of the above noted features of the interstitial waters are significant in that regard.

- o In general, to a depth of 10 centimeters, the interstitial waters are similar in composition to the overlying lake water.

- o Except for sediment core HL-2, there is an increase in dissolved solids content over the first 10 to 20 centimeter depth. The sediment chemical environment changes as a result of the decomposition of organic matter. The result of these changes could possibly bring about the dissolution of the major elements (Ca, Mg, Na, Cl) into the interstitial waters. These reactions can also be caused by the degrading action of the microorganisms. The decrease

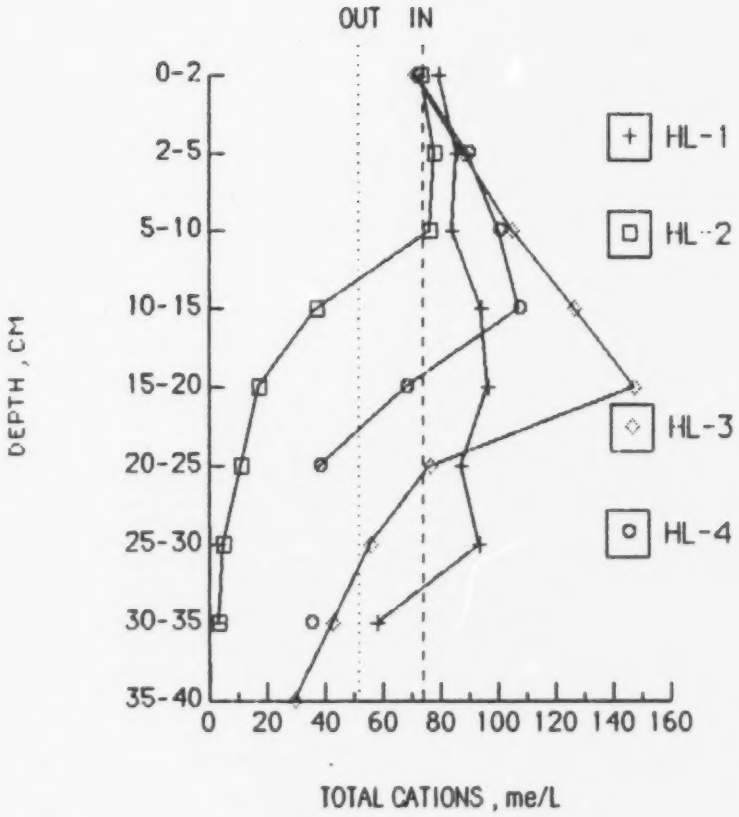


FIGURE 11

TOTAL CATIONIC CONCENTRATIONS IN THE INTERSTITIAL WATERS OF HORSESHOE POND SEDIMENT PLOTTED AS A FUNCTION OF DEPTH

The total cationic concentrations measured in the surface water at the inlet and outlet locations of Horseshoe Pond are indicated.

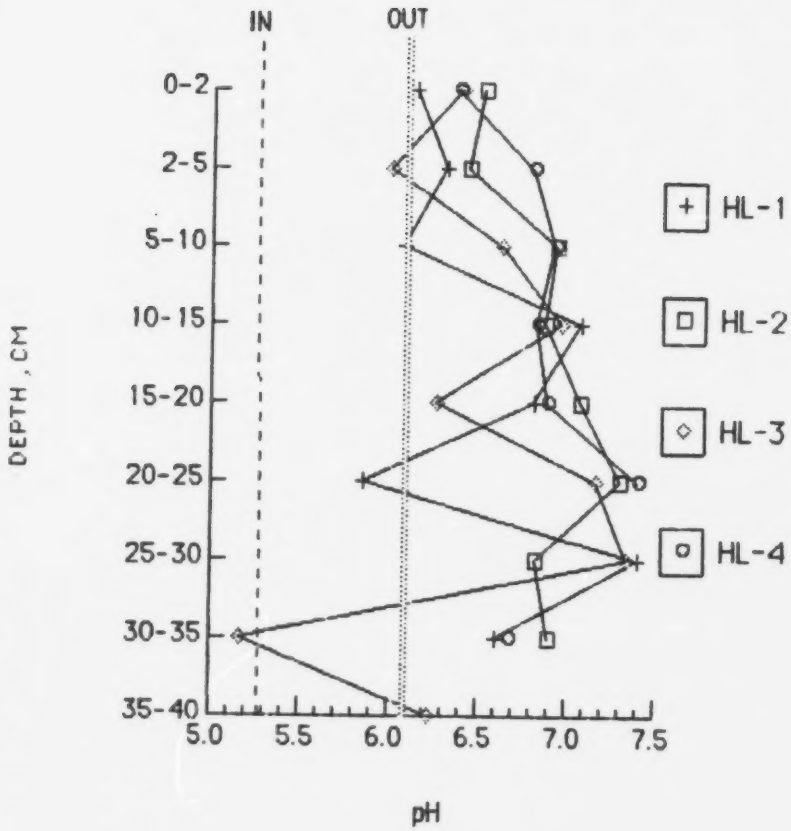


FIGURE 12

pH OF INTERSTITIAL WATERS OF HORSESHOE POND SEDIMENT AS A FUNCTION OF DEPTH

The values of the surface waters at the inlet and outlet locations of Horseshoe Pond are indicated.

in organic matter content of the sediment taken from Horseshoe Pond, with depth (see Figure 13A to D), supports this mechanism.

- Below 20 centimeters, the dissolved solids contents decrease with depth and tend toward concentrations less than the Horseshoe Pond water. Reducing conditions due to production of methane may be encouraging precipitation from solution. In support of this hypothesis, the pattern of dissolved uranium (Figure 10G) also suggests that oxygen is not present much below 2 to 5 centimeters. As discussed earlier (Section 1.1.1), uranium is more mobile in oxygenated waters and its concentration is usually lowered in the presence of reducing conditions.

- From the data obtained in this study, it appears unlikely that the upward movement of ground water through Horseshoe Pond sediment is taking place. Rather, the net downward movement of lake water into the sediment appears more likely. This hypothesis is based on the knowledge that the ground water in the area has a very low ionic content. If the net water movement was in the upward direction then the interface between the low ionic strength ground water and the higher ionic strength pond water might be expected to be close to the sediment/water interface rather than at a depth of 10 to 20 centimeters that was, in fact, observed. Net downward movement may account for the concentration profiles noted in Figures 10 and 11. This hypothesis can be confirmed by simple hydrological measurements but was not included in the terms of this study.

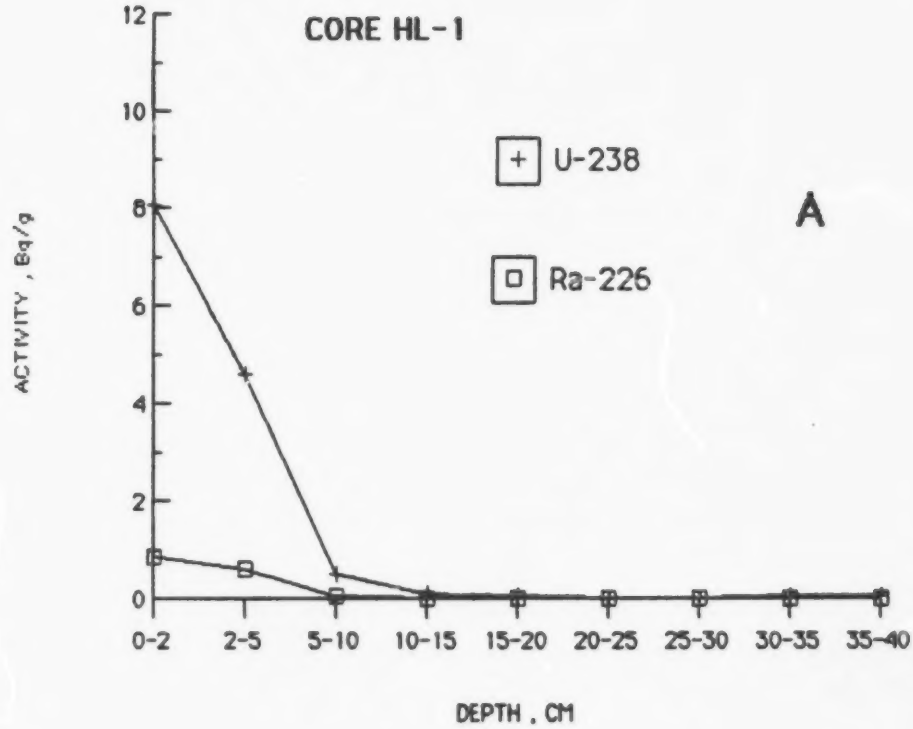
3.2 Whole Sediment Analysis

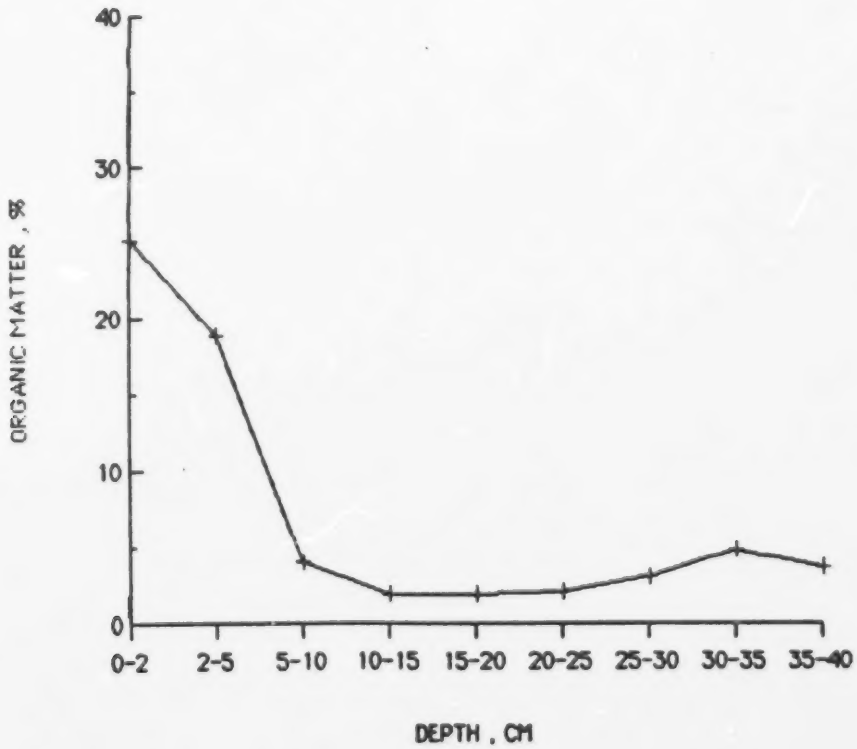
Each sediment core section was analyzed for their U-238, U-234, Th-232, Th-230, Th-228, Ra-228, Ra-226, Ra-224 and Pb-210 activity contents. The results are summarized in Table 14 along with the estimated precision of each measurement. In addition, the organic content of each, as indicated by

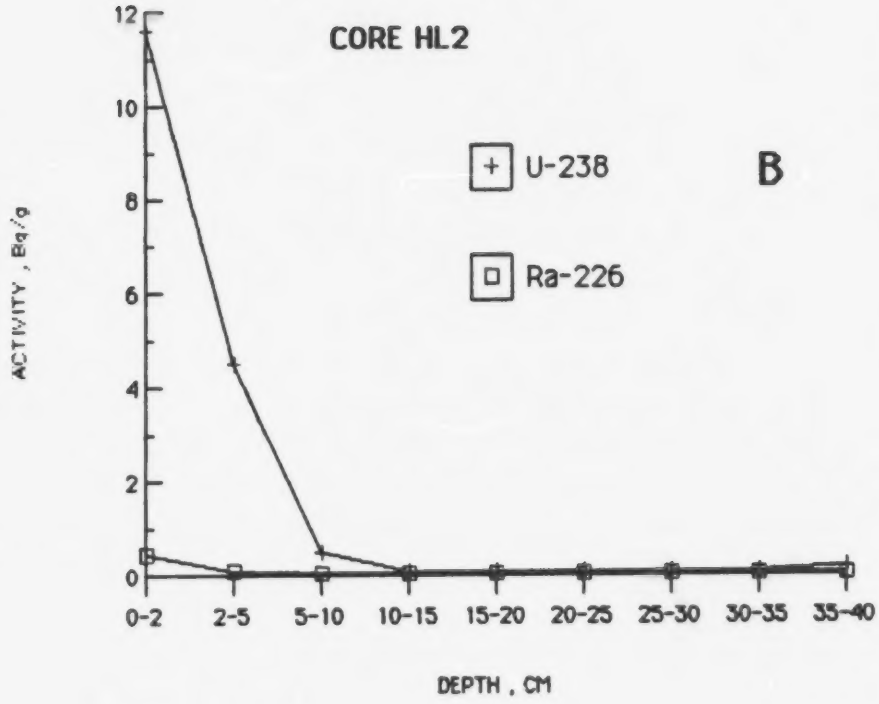
FIGURE 13

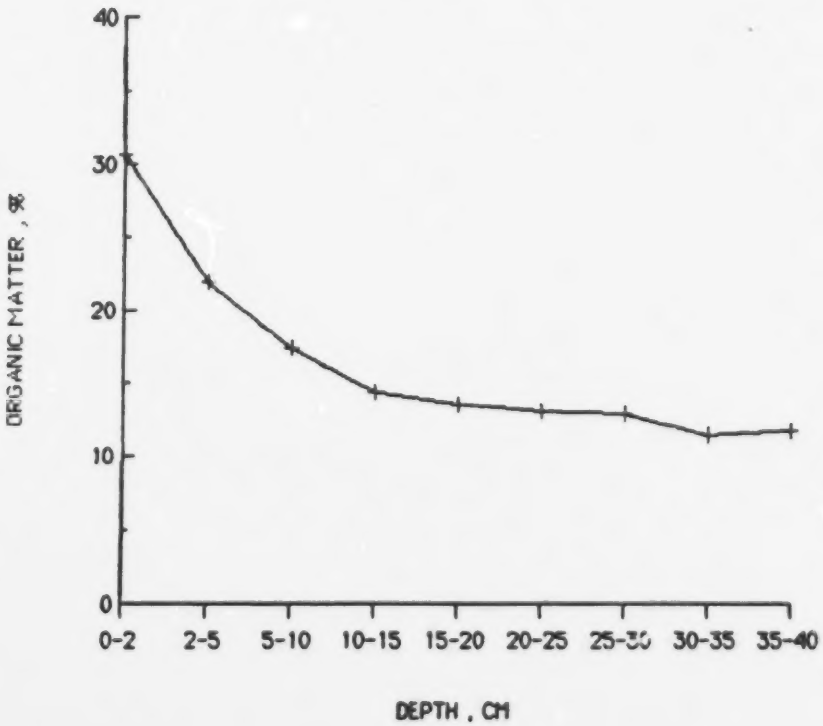
Uranium-238, Radium-226 and % Organic Matter Profiles
in Horseshoe Pond Sediments as a Function of Depth

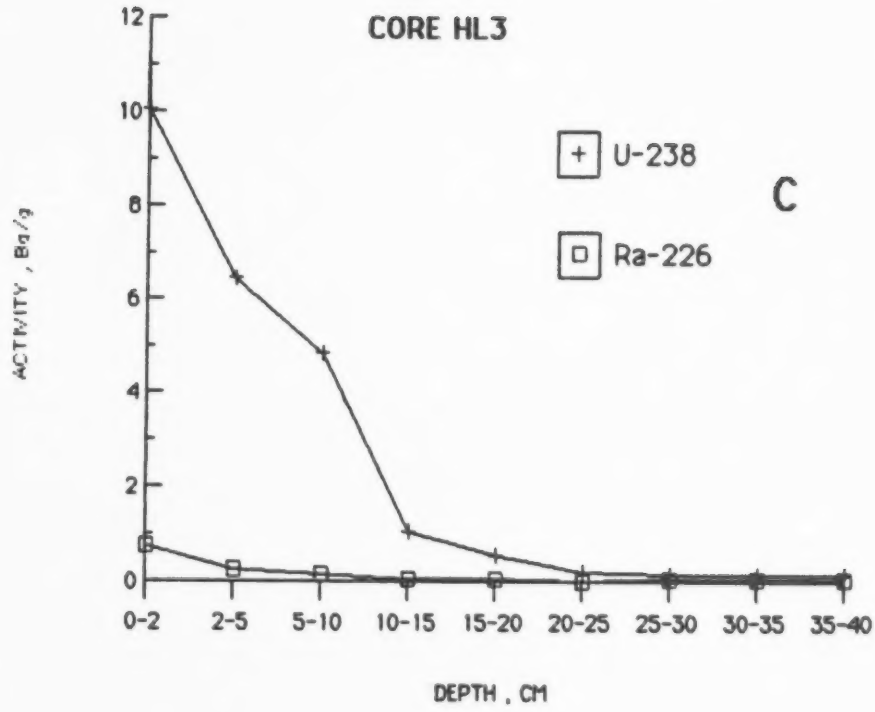
A - Core HL-1
B - Core HL-2
C - Core HL-3
D - Core HL-4

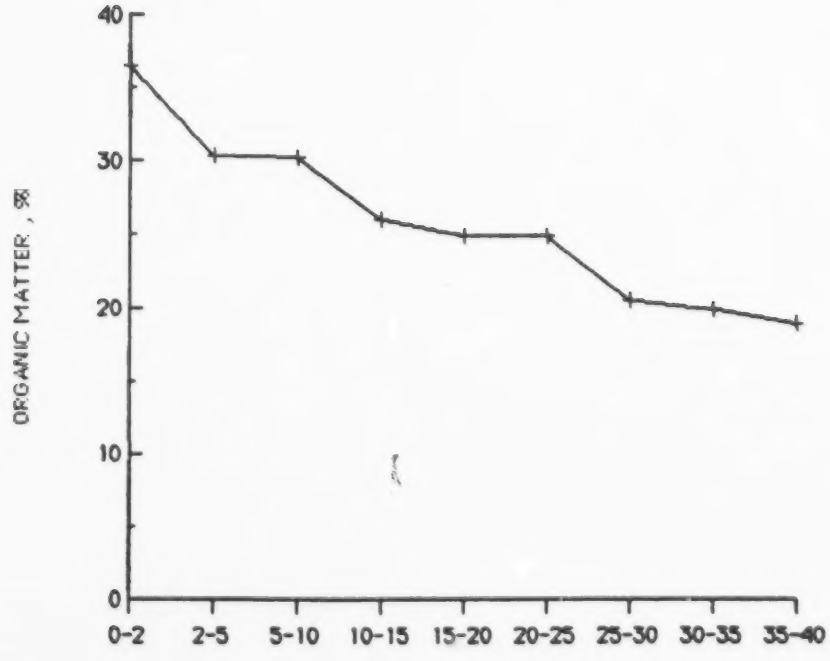

CORE HL-1
U-238
Ra-226
A
ACTIVITY , Bq/g
12
10
8
6
4
2
0
0-2
2-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
DEPTH , CM

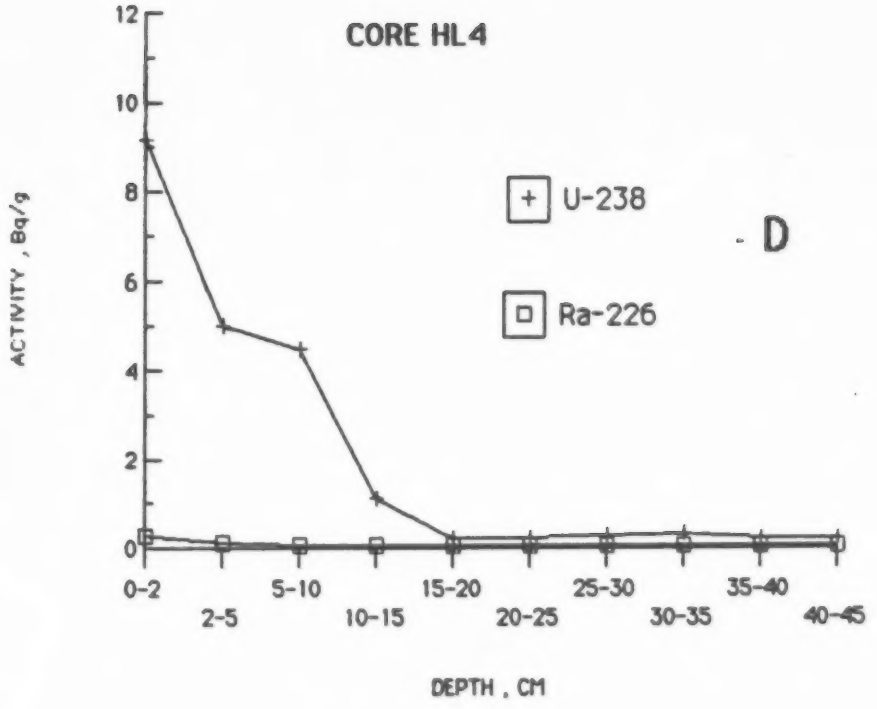

ORGANIC MATTER , %
40
30
20
10
0
0-2
2-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
DEPTH , CM


CORE HL2
U-238
Ra-226
B
ACTIVITY , Bq/g
12
10
8
6
4
2
0
0-2
2-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
DEPTH , CM


ORGANIC MATTER , %
40
30
20
10
0
0-2
2-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
DEPTH , CM


CORE HL3
U-238
Ra-226
C
ACTIVITY , Bq/g
12
10
8
6
4
2
0
0-2
2-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
DEPTH , CM


ORGANIC MATTER , %
40
30
20
10
0
0-2
2-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
DEPTH , CM


CORE HL4
U-238
Ra-226
D
ACTIVITY , Bq/g
12
10
8
6
4
2
0
0-2
2-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
DEPTH , CM

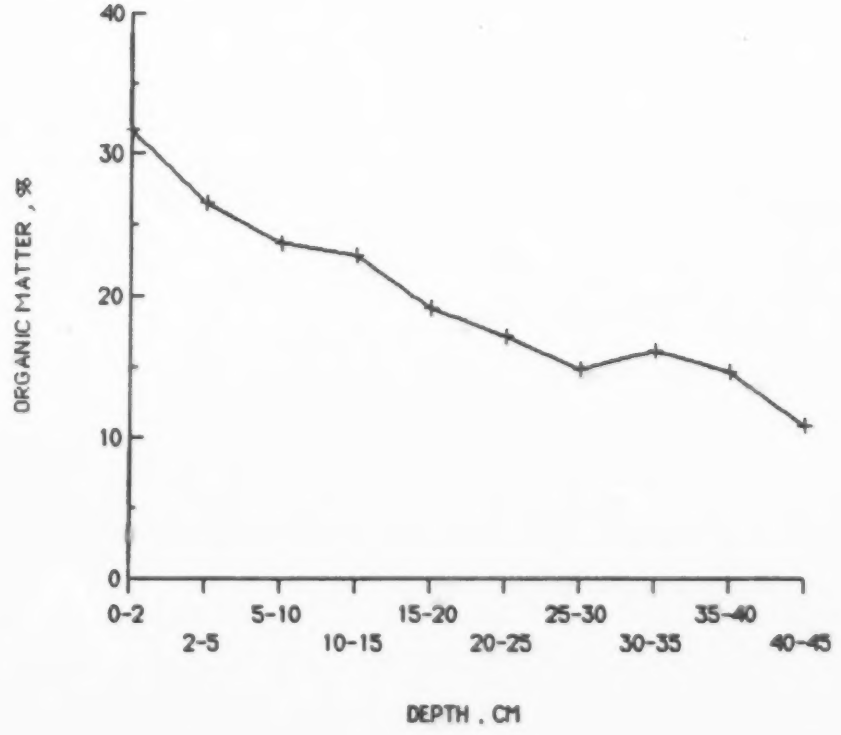

ORGANIC MATTER , %
40
30
20
10
0
0-2
2-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
DEPTH , CM

TABLE 14 Radiochemical analysis of sediment cores taken from Horseshoe Pond. All data reported on dry sediment basis.

DEPTH , CM	U ug/gram	U-234 / U-238	U-238 (calc)	Th-230	Ra-226	Pb-210	
			Bq/g(dried)				
CORE HL 1							
0-2	650 +/- 1	0.96 +/- 0.05	8.04 +/- 0.01	0.063 +/- 0.003	0.83 +/- 0.04	0.42 +/- 0.03	
2-5	372 +/- 1	0.96 +/- 0.05	4.60 +/- 0.01	0.029 +/- 0.003	0.58 +/- 0.06	0.19 +/- 0.01	
5-10	41 +/- 1	0.98 +/- 0.06	0.51 +/- 0.01	<0.010	0.07 +/- 0.01	<0.1	
10-15	7.5 +/- 0.5	1.24 +/- 0.08	0.09 +/- 0.01	<0.010	0.02 +/- 0.01	<0.1	
15-20	2.5 +/- 0.5	1.01 +/- 0.05	0.03 +/- 0.01	<0.010	0.02 +/- 0.01	<0.1	
20-25	1.2 +/- 0.5	IS	0.01 +/- 0.01	<0.010	0.02 +/- 0.01	<0.1	
25-30	2.0 +/- 0.5	0.9 +/- 0.1	0.02 +/- 0.01	<0.010	0.01 +/- 0.01	<0.1	
30-35	2.7 +/- 0.5	1.1 +/- 0.1	0.03 +/- 0.01	<0.010	<0.01	<0.1	
35-40	2.7 +/- 0.5	0.95 +/- 0.08	0.03 +/- 0.01	<0.010	0.02 +/- 0.01	<0.1	
CORE HL 2							
0-2	938 +/- 10	1.02 +/- 0.03	11.60 +/- 0.12	0.070 +/- 0.004	0.458 +/- 0.016	0.35 +/- 0.02	
2-5	365 +/- 1	0.94 +/- 0.05	4.52 +/- 0.01	0.034 +/- 0.002	0.12 +/- 0.01	0.18 +/- 0.01	
5-10	41 +/- 1	0.97 +/- 0.08	0.51 +/- 0.01	0.020 +/- 0.002	0.04 +/- 0.01	<0.1	
10-15	9.9 +/- 0.5	1.12 +/- 0.08	0.12 +/- 0.01	0.024 +/- 0.002	0.03 +/- 0.01	<0.1	
15-20	8.5 +/- 0.5	1.38 +/- 0.09	0.11 +/- 0.01	0.027 +/- 0.002	0.03 +/- 0.01	<0.1	
20-25	7.6 +/- 0.5	1.03 +/- 0.08	0.09 +/- 0.01	0.033 +/- 0.005	0.031 +/- 0.004	<0.1	
25-30	7.9 +/- 0.5	0.91 +/- 0.08	0.10 +/- 0.01	0.024 +/- 0.002	0.027 +/- 0.004	<0.1	
30-35	8.7 +/- 0.5	1.15 +/- 0.09	0.11 +/- 0.01	0.017 +/- 0.002	0.039 +/- 0.004	<0.1	
35-40	16.4 +/- 0.5	1.06 +/- 0.08	0.20 +/- 0.01	0.019 +/- 0.002	0.043 +/- 0.005	<0.1	
CORE HL 3							
0-2	811 +/- 10	1.07 +/- 0.04	10.03 +/- 0.12	0.067 +/- 0.005	0.77 +/- 0.04	0.26 +/- 0.02	
2-5	523 +/- 1	1.02 +/- 0.05	6.47 +/- 0.01	0.054 +/- 0.005	0.24 +/- 0.01	0.15 +/- 0.02	
5-10	393 +/- 1	1.01 +/- 0.04	4.86 +/- 0.01	0.037 +/- 0.005	0.14 +/- 0.01	0.18 +/- 0.02	
10-15	85 +/- 1	1.06 +/- 0.06	1.05 +/- 0.01	0.025 +/- 0.005	0.05 +/- 0.01	<0.1	
15-20	45 +/- 1	1.01 +/- 0.08	0.56 +/- 0.01	0.030 +/- 0.005	0.03 +/- 0.01	<0.1	
20-25	18 +/- 1	1.13 +/- 0.09	0.22 +/- 0.01	0.034 +/- 0.005	0.024 +/- 0.005	<0.1	
25-30	11 +/- 1	1.11 +/- 0.09	0.14 +/- 0.01	0.027 +/- 0.005	0.034 +/- 0.005	<0.1	
30-35	11 +/- 1	1.16 +/- 0.09	0.14 +/- 0.01	0.022 +/- 0.005	0.061 +/- 0.009	<0.1	
35-40	13 +/- 1	1.07 +/- 0.09	0.16 +/- 0.01	0.030 +/- 0.005	0.067 +/- 0.009	<0.1	
CORE HL 4							
0-2	740 +/- 10	1.01 +/- 0.04	9.15 +/- 0.12	0.060 +/- 0.005	0.28 +/- 0.01	0.23 +/- 0.02	
2-5	406 +/- 1	1.04 +/- 0.03	5.02 +/- 0.01	0.047 +/- 0.005	0.09 +/- 0.01	<0.1	
5-10	363 +/- 1	1.00 +/- 0.03	4.49 +/- 0.01	0.075 +/- 0.005	0.06 +/- 0.01	<0.1	
10-15	87 +/- 1	1.05 +/- 0.04	1.08 +/- 0.01	0.033 +/- 0.005	0.03 +/- 0.01	<0.1	
15-20	18 +/- 1	1.11 +/- 0.08	0.22 +/- 0.01	0.041 +/- 0.005	0.04 +/- 0.01	<0.1	
20-25	19 +/- 1	1.16 +/- 0.08	0.24 +/- 0.01	0.038 +/- 0.005	0.049 +/- 0.005	<0.1	
25-30	20 +/- 1	1.00 +/- 0.08	0.25 +/- 0.01	0.040 +/- 0.005	0.048 +/- 0.005	<0.1	
30-35	24 +/- 1	1.07 +/- 0.06	0.29 +/- 0.01	0.019 +/- 0.005	0.053 +/- 0.005	<0.1	
35-40	19 +/- 1	1.07 +/- 0.08	0.24 +/- 0.01	0.028 +/- 0.005	0.049 +/- 0.006	<0.1	
40-45	19 +/- 1	1.21 +/- 0.09	0.23 +/- 0.01	0.022 +/- 0.005	0.059 +/- 0.007	<0.1	

Pond. All data reported on dry sediment basis.

	Bq/g(dried)						% Organic
-230	Ra-226	Pb-210	Th-232	Th-228	Ra-224	Ra-228	(H202 procedure)
+/- 0.003	0.83 +/- 0.04	0.42 +/- 0.03	0.015 +/- 0.002	0.022 +/- 0.002	0.015 +/- 0.005	<0.06	25.1 +/- 0.2
+/- 0.003	0.58 +/- 0.06	0.19 +/- 0.01	0.014 +/- 0.004	0.020 +/- 0.004	0.015 +/- 0.005	<0.06	18.9 +/- 0.2
	0.07 +/- 0.01	< 0.1	0.021 +/- 0.004	0.029 +/- 0.006	0.041 +/- 0.005	<0.06	4.1 +/- 0.2
	0.02 +/- 0.01	< 0.1	0.014 +/- 0.004	0.019 +/- 0.004	0.008 +/- 0.005	<0.06	1.9 +/- 0.2
	0.02 +/- 0.01	< 0.1	<0.010	<0.010	< 0.01	<0.06	2.0 +/- 0.2
	0.02 +/- 0.01	< 0.1	0.013 +/- 0.002	0.018 +/- 0.003	0.015 +/- 0.005	<0.06	2.1 +/- 0.2
	0.01 +/- 0.01	< 0.1	0.013 +/- 0.002	0.019 +/- 0.003	0.015 +/- 0.005	<0.06	3.1 +/- 0.2
	<0.01	< 0.1	<0.010	<0.010	< 0.01	<0.06	4.9 +/- 0.2
	0.02 +/- 0.01	< 0.1	0.018 +/- 0.003	0.017 +/- 0.003	0.023 +/- 0.005	<0.06	3.7 +/- 0.2
+/- 0.004	0.458 +/- 0.016	0.35 +/- 0.02	0.020 +/- 0.002	0.020 +/- 0.002	0.018 +/- 0.005	<0.06	30.6 +/- 0.2
+/- 0.002	0.12 +/- 0.01	0.18 +/- 0.01	0.016 +/- 0.002	0.012 +/- 0.002	< 0.01	<0.06	21.9 +/- 0.2
+/- 0.002	0.04 +/- 0.01	< 0.1	0.016 +/- 0.002	0.016 +/- 0.002	0.018 +/- 0.005	<0.06	17.4 +/- 0.2
+/- 0.002	0.03 +/- 0.01	< 0.1	0.015 +/- 0.002	0.031 +/- 0.002	0.016 +/- 0.005	<0.06	14.4 +/- 0.2
+/- 0.002	0.03 +/- 0.01	< 0.1	0.020 +/- 0.002	0.026 +/- 0.002	0.019 +/- 0.005	<0.06	13.6 +/- 0.2
+/- 0.005	0.031 +/- 0.004	< 0.1	0.028 +/- 0.002	0.036 +/- 0.002	0.034 +/- 0.005	<0.06	13.1 +/- 0.2
+/- 0.002	0.027 +/- 0.004	< 0.1	0.026 +/- 0.002	0.026 +/- 0.002	0.019 +/- 0.005	<0.06	12.9 +/- 0.2
+/- 0.002	0.039 +/- 0.004	< 0.1	0.017 +/- 0.002	0.010 +/- 0.002	<0.01	<0.06	11.5 +/- 0.2
+/- 0.002	0.043 +/- 0.005	< 0.1	0.024 +/- 0.002	0.018 +/- 0.002	0.017 +/- 0.005	<0.06	11.7 +/- 0.2
+/- 0.005	0.77 +/- 0.04	0.26 +/- 0.02	0.021 +/- 0.007	0.014 +/- 0.005	< 0.01	<0.06	36.4 +/- 0.2
+/- 0.005	0.24 +/- 0.01	0.15 +/- 0.02	0.024 +/- 0.005	0.027 +/- 0.005	0.015 +/- 0.005	<0.06	30.4 +/- 0.2
+/- 0.005	0.14 +/- 0.01	0.18 +/- 0.02	<0.010	0.018 +/- 0.005	0.015 +/- 0.005	<0.06	30.1 +/- 0.2
+/- 0.005	0.05 +/- 0.01	<0.1	0.013 +/- 0.004	0.013 +/- 0.005	0.018 +/- 0.005	<0.06	26.0 +/- 0.2
+/- 0.005	0.03 +/- 0.01	< 0.1	0.013 +/- 0.004	0.020 +/- 0.005	0.017 +/- 0.005	<0.06	24.9 +/- 0.2
+/- 0.005	0.024 +/- 0.005	< 0.1	<0.010	0.023 +/- 0.005	0.033 +/- 0.005	<0.06	24.9 +/- 0.2
+/- 0.005	0.034 +/- 0.005	<0.1	0.029 +/- 0.006	0.029 +/- 0.006	0.031 +/- 0.005	<0.06	20.5 +/- 0.2
+/- 0.005	0.061 +/- 0.009	< 0.1	0.025 +/- 0.007	<0.010	0.015 +/- 0.005	<0.06	19.8 +/- 0.2
+/- 0.005	0.067 +/- 0.009	<0.1	0.020 +/- 0.004	0.020 +/- 0.006	0.021 +/- 0.005	<0.06	18.9 +/- 0.2
+/- 0.005	0.28 +/- 0.01	0.23 +/- 0.02	0.025 +/- 0.005	0.018 +/- 0.005	0.015 +/- 0.005	<0.06	31.7 +/- 0.2
+/- 0.005	0.09 +/- 0.01	< 0.1	0.015 +/- 0.005	0.016 +/- 0.005	0.015 +/- 0.005	<0.06	26.5 +/- 0.2
+/- 0.005	0.06 +/- 0.01	< 0.1	0.024 +/- 0.005	0.025 +/- 0.005	0.015 +/- 0.005	<0.06	23.6 +/- 0.2
+/- 0.005	0.03 +/- 0.01	< 0.1	0.017 +/- 0.005	0.020 +/- 0.005	0.015 +/- 0.005	<0.06	22.8 +/- 0.2
+/- 0.005	0.04 +/- 0.01	< 0.1	0.025 +/- 0.005	0.023 +/- 0.005	0.015 +/- 0.005	<0.06	19.1 +/- 0.2
+/- 0.005	0.049 +/- 0.005	< 0.1	0.025 +/- 0.005	0.031 +/- 0.005	0.026 +/- 0.005	<0.06	17.1 +/- 0.2
+/- 0.005	0.048 +/- 0.005	< 0.1	0.019 +/- 0.005	0.041 +/- 0.005	0.016 +/- 0.005	<0.06	14.9 +/- 0.2
+/- 0.005	0.053 +/- 0.005	< 0.1	0.020 +/- 0.005	< 0.010	0.016 +/- 0.005	<0.06	16.2 +/- 0.2
+/- 0.005	0.049 +/- 0.006	< 0.1	0.019 +/- 0.005	0.023 +/- 0.006	0.024 +/- 0.005	<0.06	14.6 +/- 0.2
+/- 0.005	0.059 +/- 0.007	< 0.1	0.021 +/- 0.005	0.033 +/- 0.005	0.026 +/- 0.005	<0.06	10.8 +/- 0.2

the amount of sediment remaining after hydrogen peroxide oxidation (see Section 1.5.2), are given. A comparison of this procedure with the more standard analytical techniques for organic matter determination, loss-on-ignition (LOI) and organic carbon determination by potassium dichromate oxidation (Allison 1965), has been made and is included in Section 3.4 of this report.

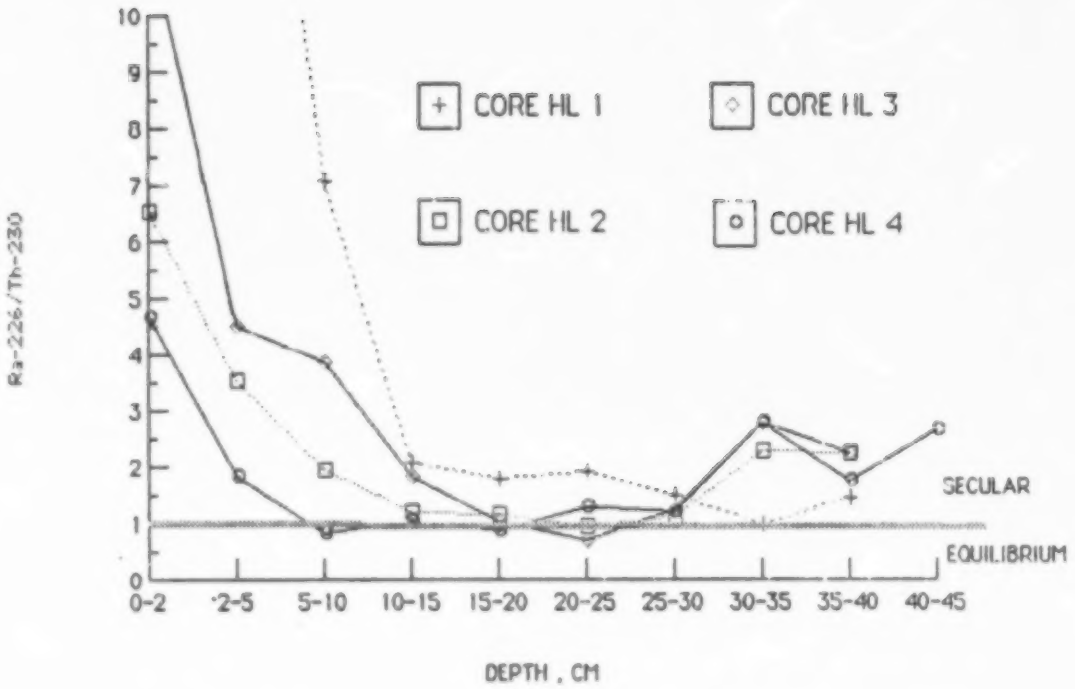
The highest activities in each core were found at shallow depth and belonged to U-238, U-234, Ra-226 and Pb-210. Figure 13 (A to D) shows the U-238 and Ra-226 activity profiles with depth for the four cores. For comparison purposes, the concentration profile for organic matter content is also shown.

In attempting to answer the questions of how the radioactive species found their way to their present location and where they originated, several features should be noted.

1) Table 14 shows that over the first 10 to 15 centimeters, the Ra-226 activity greatly exceeds the Th-230 activity while at greater depths, the activity of Ra-226 approaches that of Th-230. This behaviour is illustrated in Figure 14 where the Ra-226/Th-230 activity ratio is plotted against depth. An excess of Ra-226 relative to Th-230 can be supported by several possible mechanisms: (i) adsorption of Ra-226 from solution onto the organic phase of the sediment has taken place; (ii) adsorption of Ra-226 from solution onto the inorganic phase of the sediment has taken place; (iii) precipitation of Ra-226 from solution (possible as $RaSO_4$) has taken place; and (iv) the Ra-226 was absorbed by living terrestrial plants and after decay, subsequently found its way (via surface runoff) into the sediment. At the greater depths, where the activity of Ra-226 approaches that of Th-230, it must be strongly suggested that deposition of suspended inorganic solids, eroded from the earth's surface, is the mechanism that predominated. The possibility that this mechanism has occurred to the same extent at all depths along

FIGURE 14

Plot of Ra-226/Th-230 in Horseshoe Pond
Sediments as a Function of Depth


Ra-226/Th-230
10
9
8
7
6
5
4
3
2
1
0
CORE HL 1
CORE HL 3
CORE HL 2
CORE HL 4
SECULAR
EQUILIBRIUM
0-2
2-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
DEPTH , CM

with the mechanisms (i), (ii) and (iii) cannot be discounted. Microbial degration of organic matter at the deeper depths may be taking place leading to the movement of "released" Ra-226 toward the surface layers via re-adsorption.

2) Figure 15 is a plot of U-234/Th-230 activity ratio as a function of depth for each sediment core taken. It shows that over the first 10-20 centimeters, uranium exceeds the Th-230 activity by more than 30 times, but at the greater depths equilibrium between the two is within a factor of 10 (uranium predominant). An excess of uranium activity relative to Th-230 activity can be supported by mechanisms similar to those suggested for Ra-226 in (1) above.

3) Figure 16 is a plot of the U-234/U-238 ratio as a function of depth for each core. The data fluctuate a great deal and make it difficult to draw conclusions. It would be expected that uranium adsorbed from solution would have a U-234/U-238 ratio exceeding 1.0, while uranium deposited from the terrestrial environment or subjected to leaching would have a U-234/U-238 ratio of ≤ 1.0 (see discussion in Section 1.1.1).

4) Uranium activity in the sediment cores is greater than Ra-226 and Th-230 activities at all depths. Detectable activities of Pb-210 are measured only at shallow depths. Radium-228 is below detection limits at all depths. The ratio of Th-228/Th-232 generally exceeds or is equal to 1.0 at shallow depths. Since thorium is usually insoluble in solution, these isotopes must have arrived in the sediments either by solid deposition or by radioactive in-growth (or a combination of both). The presence of Th-228 in excess of Th-232 may be explained by the presence of Ra-228 at the shallow depths. If Ra-228 were present it would be expected to accumulate in the sediments via the same mechanisms as Ra-226. Since Ra-228 is the parent of Th-228 and has a relatively short half-life (7 years) its

FIGURE 15

Plot of U-234/Th-230 in Horseshoe Pond
Sediments as a Function of Depth

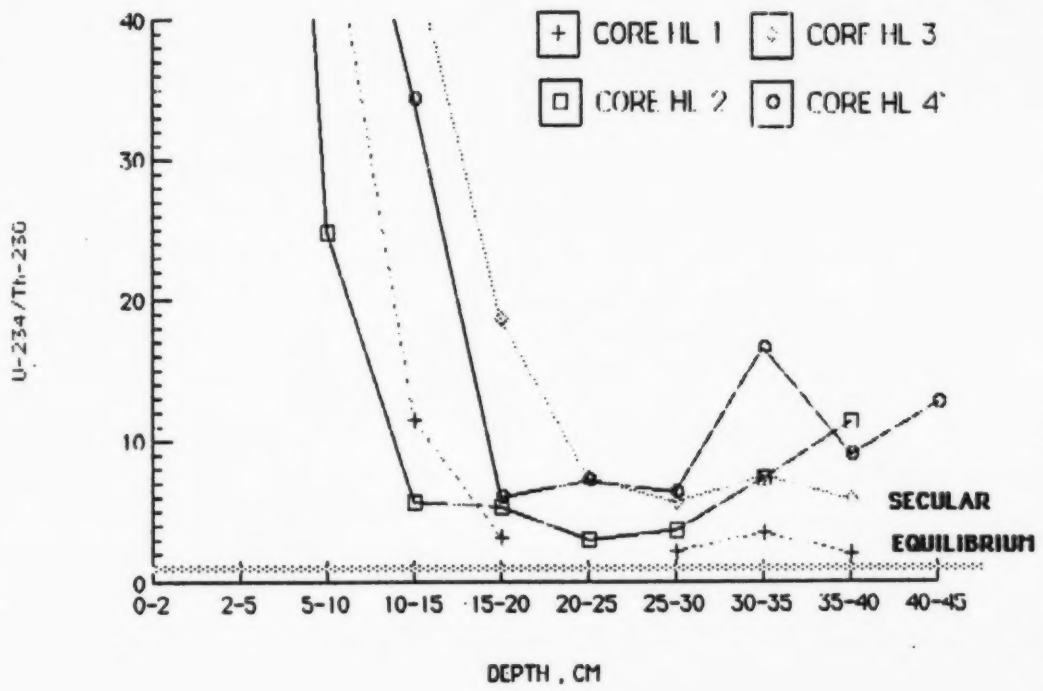
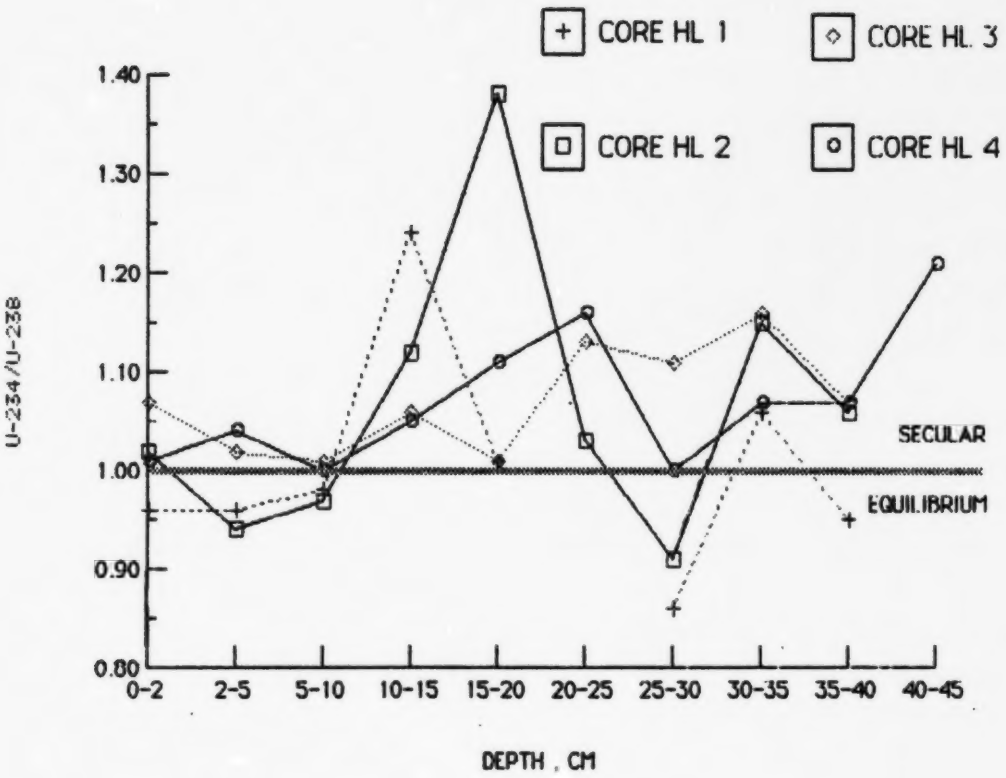


FIGURE 16

Plot of U-234/U-238 in Horseshoe Pond
Sediments as a Function of Depth



decay would result in an excess of Th-228 activity relative to Th-232 activity

5) A fifth sediment core located in Hidden Bay near the outflow from Horseshoe Pond was analyzed for its radionuclide content. The results are shown in Table 15. They show that the uranium and Ra-226 activities at the core surface are more than ten times lower than they were at the surface of the cores removed from Horseshoe Pond. Comparison with the data reported by Sawchyn in 1972 and shown earlier in Table 2, reveals close similarity for all parameters except uranium content. In 1972 Sawchyn reported 0 08 ± 0.04 Bq/g for four samples, whereas in this study 0.57 Bq/g was found in the one surface sample taken.

3.3 Separation and Analysis of the Organic and Inorganic Portions of Lake Sediments

It has been visualized (Joshi and Ganguly 1977) for the sake of modelling, that a sediment particle is a sphere comprised of an inorganic inner core and on organic outer layer. The organic matter content of the Horseshoe Pond sediments is given in Table 14. In an attempt to elucidate the mechanism of how the radionuclides arrived in the sediments the organic portion of the sediment was dissolved using the hydrogen peroxide procedure described in Section 1.5.2. This procedure is quoted often in the literature (Joshi et al. 1980, Joshi and Ganguly 1977, Kepkay 1986, Willey and Fitzgerald 1980) by researchers investigating elemental sediment distributions. The resulting solution was then analyzed for Ra-226, Pb-210, Ra-228 and U-234/U-238 ratio. The remaining inorganic phase was analyzed separately for uranium, Th-232, Th-230, Th-228, Ra-226 and Pb-210. The results of the analyses of both phases of Horseshoe Pond sediment cores are shown in Tables 16 and 17. Comparable data for the Hidden Bay core are shown in Tables 18 and 19.

TABLE 15 RADIOCHEMICAL CONTENTS OF SEDIMENT CORE TAKEN FROM HIDDEN BAY. All data is reported on basis of dry , whole sediment.

DEPTH,CM	U ug/g	U-234 / U-238	Bq/g								% Organic
			U-238 (calc)	Th-230	Ra-226	Pb-210	Th-232	Th-228	Ra-224	Ra-228	(H202 Procedure)
CORE H8E											
0-2	46.0 +/- 1	1.02 +/- 0.06	0.57 +/- 0.01	0.021 +/- 0.002	0.026 +/- 0.005	<0.2	0.021 +/- 0.002	0.023 +/- 0.002	0.021 +/- 0.005	<0.06	4.9 +/- 0.2
2-5	9.8 +/- 0.5	1.16 +/- 0.08	0.12 +/- 0.01	0.022 +/- 0.002	0.035 +/- 0.004	<0.2	0.024 +/- 0.002	0.033 +/- 0.002	0.029 +/- 0.005	<0.06	6.8 +/- 0.2
5-10	6.0 +/- 0.5	0.97 +/- 0.08	0.07 +/- 0.01	0.017 +/- 0.003	0.031 +/- 0.005	<0.2	0.027 +/- 0.003	0.038 +/- 0.003	0.036 +/- 0.005	<0.06	5.4 +/- 0.2
10-15	4.8 +/- 0.5	1.08 +/- 0.07	0.06 +/- 0.01	0.011 +/- 0.002	0.038 +/- 0.007	<0.2	0.016 +/- 0.003	0.018 +/- 0.003	0.019 +/- 0.005	<0.06	4.7 +/- 0.2
15-20	3.3 +/- 0.5	1.11 +/- 0.08	0.04 +/- 0.01	0.011 +/- 0.002	0.025 +/- 0.004	<0.2	0.021 +/- 0.003	0.021 +/- 0.003	0.019 +/- 0.005	<0.06	2.7 +/- 0.2
20-25	2.9 +/- 0.5	0.89 +/- 0.06	0.04 +/- 0.01	0.017 +/- 0.003	0.022 +/- 0.005	<0.2	0.022 +/- 0.003	0.018 +/- 0.003	0.019 +/- 0.005	<0.06	2.4 +/- 0.2

TABLE 16 RADIOCHEMICAL CONTENTS OF THE ORGANIC PORTION OF SEDIMENT CORES TAKEN FROM HORSESHOE POND. All data is reported on basis of content in dry whole sediment.

DEPTH , CM	U* ug/g	U-234 / U-238	Bq/g(dried) U-238* (calc)	Th-230*	Ra-226	Pb-210	Th-232*	Th-228*	Ra-228
CORE HL 1									
0-2	642 +/- 1	0.97 +/- 0.05	7.94 +/- 0.01	0.020 +/- 0.005	0.018 +/- 0.06	0.13 +/- 0.05	-0.006 +/- 0.003	0.009 +/- 0.003	<0.10
2-5	370 +/- 1	1.06 +/- 0.05	4.58 +/- 0.01	0.014 +/- 0.005	0.011 +/- 0.08	<0.1	0.001 +/- 0.006	0.007 +/- 0.006	<0.10
5-10	40 +/- 1	1.07 +/- 0.06	0.50 +/- 0.01	-0.002 +/- 0.005	0.037 +/- 0.02	<0.1	0.010 +/- 0.006	0.017 +/- 0.007	<0.10
10-15	6.8 +/- 0.5	0.91 +/- 0.08	0.08 +/- 0.01	0.004 +/- 0.005	0.01 +/- 0.02	<0.1	0.006 +/- 0.006	0.010 +/- 0.005	<0.10
15-20	2.3 +/- 0.5	0.92 +/- 0.05	0.03 +/- 0.01	-0.009 +/- 0.005	0.006 +/- 0.02	<0.1	-0.004 +/- 0.005	-0.011 +/- 0.005	<0.10
20-25	0.4 +/- 0.5	1.3 +/- 0.1	0.00 +/- 0.01	0.003 +/- 0.005	0.007 +/- 0.02	<0.1	0.006 +/- 0.005	0.009 +/- 0.004	<0.10
25-30	1.4 +/- 0.5	1.1 +/- 0.1	0.02 +/- 0.01	0.001 +/- 0.005	0.005 +/- 0.02	<0.1	-0.002 +/- 0.005	0.003 +/- 0.005	<0.10
30-35	2.2 +/- 0.5	1.0 +/- 0.1	0.03 +/- 0.01	0.002 +/- 0.005	0.008 +/- 0.02	<0.1	-0.001 +/- 0.005	-0.003 +/- 0.005	<0.10
35-40	2.0 +/- 0.5	0.91 +/- 0.08	0.02 +/- 0.01	0.009 +/- 0.005	0.006 +/- 0.02	<0.1	0.003 +/- 0.005	0.001 +/- 0.005	<0.10
CORE HL2									
0-2	924 +/- 10	1.01 +/- 0.03	11.43 +/- 0.12	0.034 +/- 0.005	0.021 +/- 0.03	0.16 +/- 0.03	-0.001 +/- 0.005	-0.004 +/- 0.003	<0.10
2-5	354 +/- 1	1.00 +/- 0.05	4.36 +/- 0.01	-0.002 +/- 0.005	0.015 +/- 0.02	0.12 +/- 0.02	0.002 +/- 0.005	-0.003 +/- 0.003	<0.10
5-10	39 +/- 1	0.95 +/- 0.08	0.49 +/- 0.01	0.004 +/- 0.005	0.015 +/- 0.02	<0.1	-0.002 +/- 0.005	-0.001 +/- 0.003	<0.10
10-15	8.2 +/- 0.5	0.89 +/- 0.08	0.10 +/- 0.01	0.003 +/- 0.005	0.025 +/- 0.02	<0.1	-0.003 +/- 0.005	0.012 +/- 0.003	<0.10
15-20	7.6 +/- 0.5	1.13 +/- 0.09	0.09 +/- 0.01	0.005 +/- 0.005	0.029 +/- 0.02	<0.1	-0.001 +/- 0.005	0.004 +/- 0.003	<0.10
20-25	6.9 +/- 0.5	1.10 +/- 0.08	0.09 +/- 0.01	0.016 +/- 0.005	0.026 +/- 0.006	<0.1	0.014 +/- 0.005	0.018 +/- 0.003	<0.10
25-30	7.0 +/- 0.5	1.05 +/- 0.08	0.09 +/- 0.01	0.003 +/- 0.005	0.029 +/- 0.006	<0.1	0.013 +/- 0.005	-0.01 +/- 0.003	<0.10
30-35	7.6 +/- 0.5	1.08 +/- 0.09	0.09 +/- 0.01	-0.006 +/- 0.005	0.035 +/- 0.006	<0.1	-0.002 +/- 0.005	-0.011 +/- 0.003	<0.10
35-40	15.3 +/- 0.5	1.10 +/- 0.08	0.19 +/- 0.01	-0.006 +/- 0.005	0.036 +/- 0.006	<0.1	0.005 +/- 0.005	-0.005 +/- 0.003	<0.10
CORE HL3									
0-2	796 +/- 10	1.02 +/- 0.04	9.84 +/- 0.12	0.042 +/- 0.005	0.005 +/- 0.06	<0.1	0.003 +/- 0.008	-0.007 +/- 0.007	<0.10
2-5	511 +/- 1	1.02 +/- 0.05	6.32 +/- 0.01	0.023 +/- 0.005	0.004 +/- 0.02	0.12 +/- 0.02	0.007 +/- 0.005	0.006 +/- 0.007	<0.10
5-10	385 +/- 1	1.07 +/- 0.04	4.76 +/- 0.01	0.006 +/- 0.005	0.003 +/- 0.02	<0.1	-0.005 +/- 0.005	0.004 +/- 0.007	<0.10
10-15	82 +/- 1	1.05 +/- 0.06	1.02 +/- 0.01	0.006 +/- 0.005	0.009 +/- 0.02	<0.1	0.001 +/- 0.005	-0.003 +/- 0.007	<0.10
15-20	43 +/- 1	1.01 +/- 0.08	0.53 +/- 0.01	0.003 +/- 0.005	0.009 +/- 0.02	<0.1	0.001 +/- 0.005	0.004 +/- 0.007	<0.10
20-25	17 +/- 1	1.15 +/- 0.09	0.21 +/- 0.01	0.012 +/- 0.005	0.015 +/- 0.007	<0.1	-0.006 +/- 0.005	0.007 +/- 0.007	<0.10
25-30	10 +/- 1	1.12 +/- 0.09	0.13 +/- 0.01	0.013 +/- 0.005	0.023 +/- 0.007	<0.1	0.011 +/- 0.007	0.008 +/- 0.007	<0.10
30-35	10 +/- 1	1.17 +/- 0.09	0.13 +/- 0.01	-0.009 +/- 0.005	0.031 +/- 0.01	<0.1	0.008 +/- 0.009	-0.017 +/- 0.007	<0.10
35-40	12 +/- 1	1.09 +/- 0.09	0.15 +/- 0.01	0.030 +/- 0.005	0.045 +/- 0.01	<0.1	0.02 +/- 0.005	0.020 +/- 0.007	<0.10
CORE HL4									
0-2	726 +/- 10	1.13 +/- 0.04	8.98 +/- 0.12	0.022 +/- 0.005	0.011 +/- 0.02	<0.1	0.014 +/- 0.005	0.001 +/- 0.008	<0.10
2-5	396 +/- 1	1.08 +/- 0.03	4.90 +/- 0.01	0.003 +/- 0.005	0.014 +/- 0.02	<0.1	0.007 +/- 0.005	-0.001 +/- 0.008	<0.10
5-10	353 +/- 1	1.17 +/- 0.03	4.36 +/- 0.01	0.014 +/- 0.005	0.023 +/- 0.02	<0.1	0.01 +/- 0.005	0.002 +/- 0.008	<0.10
10-15	84 +/- 1	1.17 +/- 0.04	1.05 +/- 0.01	0.002 +/- 0.005	0.034 +/- 0.02	<0.1	-0.004 +/- 0.005	0.001 +/- 0.008	<0.10
15-20	17 +/- 1	1.14 +/- 0.08	0.21 +/- 0.01	0.010 +/- 0.005	0.041 +/- 0.02	<0.1	0.006 +/- 0.005	0.002 +/- 0.008	<0.10
20-25	18 +/- 1	1.15 +/- 0.08	0.23 +/- 0.01	-0.001 +/- 0.005	0.039 +/- 0.006	<0.1	0.003 +/- 0.005	0.006 +/- 0.008	<0.10
25-30	19 +/- 1	1.17 +/- 0.08	0.24 +/- 0.01	0.040 +/- 0.005	0.037 +/- 0.006	<0.1	0.019 +/- 0.005	0.041 +/- 0.008	<0.10
30-35	23 +/- 1	1.02 +/- 0.06	0.28 +/- 0.01	0.019 +/- 0.005	0.052 +/- 0.006	<0.1	0.02 +/- 0.005	0.010 +/- 0.008	<0.10
35-40	18 +/- 1	1.16 +/- 0.08	0.23 +/- 0.01	0.028 +/- 0.005	0.034 +/- 0.006	<0.1	0.019 +/- 0.005	0.023 +/- 0.008	<0.10
40-45	18 +/- 1	0.96 +/- 0.09	0.23 +/- 0.01	0.022 +/- 0.005	0.043 +/- 0.006	<0.1	0.021 +/- 0.005	0.033 +/- 0.008	<0.10

* Calculated difference between whole sediment content and inorganic phase content.

TABLE 17 RADIOCHEMICAL CONTENTS OF THE INORGANIC PORTION OF SEDIMENT CORES TAKEN FROM HORSESHOE POND. All data reported on basis of dry, whole sediment.

DEPTH , CM	U ug/g	Bq/g(dried) U-238 (calc)	Th-230	Ra-226	Pb-210	Th-232	Th-228
	CORE HL1						
0-2	7.8 +/- 0.5	0.096 +/- 0.006	0.043 +/- 0.003	0.69 +/- 0.08	0.29 +/- 0.05	0.021 +/- 0.002	0.013 +/- 0.002
2-5	1.5 +/- 0.5	0.019 +/- 0.006	0.015 +/- 0.003	0.44 +/- 0.02	<0.15	0.013 +/- 0.002	0.013 +/- 0.002
5-10	0.8 +/- 0.1	0.010 +/- 0.001	0.012 +/- 0.002	0.019 +/- 0.005	<0.15	0.011 +/- 0.002	0.012 +/- 0.002
10-15	0.7 +/- 0.1	0.009 +/- 0.001	0.006 +/- 0.002	0.008 +/- 0.002	<0.15	0.008 +/- 0.002	0.009 +/- 0.002
15-20	0.2 +/- 0.1	0.002 +/- 0.001	0.019 +/- 0.003	0.014 +/- 0.003	<0.15	0.014 +/- 0.001	0.021 +/- 0.003
20-25	0.8 +/- 0.1	0.010 +/- 0.001	0.007 +/- 0.001	0.015 +/- 0.004	<0.15	0.007 +/- 0.001	0.009 +/- 0.001
25-30	0.6 +/- 0.1	0.007 +/- 0.001	0.009 +/- 0.001	0.005	<0.15	0.015 +/- 0.001	0.016 +/- 0.001
30-35	0.5 +/- 0.1	0.006 +/- 0.001	0.008 +/- 0.001	0.011 +/- 0.004	<0.15	0.011 +/- 0.001	0.013 +/- 0.001
35-40	0.7 +/- 0.1	0.009 +/- 0.001	0.007 +/- 0.002	0.014 +/- 0.004	<0.15	0.015 +/- 0.002	0.016 +/- 0.002
	CORE HL2						
0-2	13.9 +/- 0.5	0.172 +/- 0.006	0.036 +/- 0.004	0.401 +/- 0.015	0.19 +/- 0.05	0.021 +/- 0.003	0.024 +/- 0.003
2-5	10.6 +/- 0.5	0.131 +/- 0.006	0.036 +/- 0.004	0.122 +/- 0.013	<0.15	0.014 +/- 0.002	0.015 +/- 0.002
5-10	2.0 +/- 0.5	0.025 +/- 0.006	0.016 +/- 0.002	0.026 +/- 0.002	<0.15	0.018 +/- 0.002	0.017 +/- 0.002
10-15	1.7 +/- 0.1	0.021 +/- 0.001	0.021 +/- 0.003	0.021 +/- 0.001	<0.15	0.018 +/- 0.003	0.019 +/- 0.003
15-20	0.9 +/- 0.1	0.011 +/- 0.001	0.022 +/- 0.003	0.013 +/- 0.004	<0.15	0.021 +/- 0.003	0.022 +/- 0.003
20-25	0.7 +/- 0.1	0.009 +/- 0.001	0.017 +/- 0.003	0.013 +/- 0.004	<0.15	0.014 +/- 0.003	0.018 +/- 0.003
25-30	0.9 +/- 0.1	0.011 +/- 0.001	0.021 +/- 0.002	0.015 +/- 0.004	<0.15	0.013 +/- 0.002	0.036 +/- 0.002
30-35	1.1 +/- 0.1	0.014 +/- 0.001	0.023 +/- 0.003	0.014 +/- 0.004	<0.15	0.019 +/- 0.003	0.021 +/- 0.003
35-40	1.1 +/- 0.1	0.014 +/- 0.001	0.025 +/- 0.002	0.017 +/- 0.004	<0.15	0.019 +/- 0.002	0.023 +/- 0.002
	CORE HL3						
0-2	15.3 +/- 0.5	0.189 +/- 0.006	0.025 +/- 0.003	0.81 +/- 0.08	0.26 +/- 0.05	0.018 +/- 0.003	0.021 +/- 0.003
2-5	12.2 +/- 0.5	0.151 +/- 0.006	0.031 +/- 0.003	0.269 +/- 0.015	<0.15	0.017 +/- 0.003	0.021 +/- 0.003
5-10	7.9 +/- 0.5	0.098 +/- 0.006	0.031 +/- 0.003	0.141 +/- 0.014	<0.15	0.015 +/- 0.003	0.014 +/- 0.003
10-15	3.2 +/- 0.5	0.040 +/- 0.006	0.019 +/- 0.003	0.043 +/- 0.001	<0.15	0.012 +/- 0.003	0.016 +/- 0.003
15-20	2.1 +/- 0.5	0.026 +/- 0.006	0.027 +/- 0.003	0.026 +/- 0.002	<0.15	0.012 +/- 0.003	0.016 +/- 0.003
20-25	1.2 +/- 0.1	0.015 +/- 0.001	0.022 +/- 0.002	0.026 +/- 0.002	<0.15	0.016 +/- 0.002	0.016 +/- 0.002
25-30	1.1 +/- 0.1	0.014 +/- 0.001	0.014 +/- 0.002	0.016 +/- 0.004	<0.15	0.018 +/- 0.002	0.021 +/- 0.002
30-35	1.2 +/- 0.1	0.015 +/- 0.001	0.031 +/- 0.003	0.021 +/- 0.004	<0.15	0.017 +/- 0.003	0.027 +/- 0.003
35-40	1.1 +/- 0.1	0.014 +/- 0.001	0.035 +/- 0.002	0.011 +/- 0.005	<0.15	0.024 +/- 0.002	0.025 +/- 0.002
	CORE HL4						
0-2	14.3 +/- 0.5	0.177 +/- 0.006	0.038 +/- 0.003	0.27 +/- 0.03	0.23 +/- 0.05	0.011 +/- 0.003	0.017 +/- 0.003
2-5	9.8 +/- 0.5	0.121 +/- 0.006	0.044 +/- 0.003	0.096 +/- 0.012	<0.15	0.008 +/- 0.003	0.017 +/- 0.003
5-10	10.2 +/- 0.5	0.126 +/- 0.006	0.061 +/- 0.003	0.049 +/- 0.001	<0.15	0.014 +/- 0.003	0.023 +/- 0.003
10-15	2.8 +/- 0.5	0.035 +/- 0.006	0.031 +/- 0.003	0.009 +/- 0.003	<0.15	0.021 +/- 0.003	0.019 +/- 0.003
15-20	1.1 +/- 0.1	0.014 +/- 0.001	0.031 +/- 0.002	0.012 +/- 0.003	<0.15	0.019 +/- 0.002	0.021 +/- 0.002
20-25	0.8 +/- 0.1	0.010 +/- 0.001	0.039 +/- 0.002	0.007 +/- 0.003	<0.15	0.022 +/- 0.002	0.025 +/- 0.002
25-30	0.9 +/- 0.1	0.011 +/- 0.001	0.034 +/- 0.002	0.011 +/- 0.005	<0.15	0.019 +/- 0.002	0.018 +/- 0.002
30-35	1.1 +/- 0.1	0.014 +/- 0.001	0.034 +/- 0.004	0.005	<0.15	0.023 +/- 0.003	0.023 +/- 0.003
35-40	0.7 +/- 0.1	0.009 +/- 0.001	0.031 +/- 0.004	0.011 +/- 0.002	<0.15	0.014 +/- 0.003	0.016 +/- 0.003
40-45	1.1 +/- 0.1	0.014 +/- 0.001	0.028 +/- 0.004	0.011 +/- 0.002	<0.15	0.019 +/- 0.003	0.018 +/- 0.003

TABLE 18 RADIOCHEMICAL CONTENTS OF THE ORGANIC PORTION OF SEDIMENT CORES TAKEN FROM HIDDEN BAY. All data reported on basis of dry whole sediment.

DEPTH,CM	U* ug/g	U-234 / U-238	Bq/g						
			U-238* (calc)	Th-230*	Ra-226	Pb-210	Th-232*	Th-228*	Ra-228
CORE H6E									
0-2	43.7 +/- 1	0.95 +/- 0.05	0.54 +/- 0.01	0.006 +/- 0.002	0.015 +/- 0.002	<0.2	0.003 +/- 0.003	0.001 +/- 0.003	<0.1
2-5	7.9 +/- 0.5	1.03 +/- 0.07	0.10 +/- 0.01	0.001 +/- 0.002	0.015 +/- 0.002	<0.2	0.003 +/- 0.003	0.004 +/- 0.003	<0.1
5-10	4.8 +/- 0.5	1.18 +/- 0. 9	0.06 +/- 0.01	0.000 +/- 0.004	0.016 +/- 0.003	<0.2	0.010 +/- 0.005	0.022 +/- 0.005	<0.1
10-15	3.4 +/- 0.5	1.02 +/- 0.07	0.04 +/- 0.01	-0.005 +/- 0.004	0.017 +/- 0.002	<0.2	0.000 +/- 0.005	-0.006 +/- 0.005	<0.1
15-20	1.9 +/- 0.5	1.09 +/- 0.08	0.02 +/- 0.01	0.000 +/- 0.003	0.011 +/- 0.001	<0.2	0.003 +/- 0.005	0.003 +/- 0.005	<0.1
20-25	1.9 +/- 0.5	1.08 +/- 0.07	0.02 +/- 0.01	0.005 +/- 0.003	0.011 +/- 0.001	<0.2	0.005 +/- 0.005	-0.001 +/- 0.005	<0.1

*CALCULATED DIFFERENCE BETWEEN WHOLE SEDIMENT CONTENT AND INORGANIC PHASE CONTENT

Table 19 RADIOCHEMICAL CONTENTS OF THE INORGANIC PORTION OF SEDIMENT CORES TAKEN FROM HIDDEN BAY. All data reported on basis of dry, whole sediment.

DEPTH,CM	U ug/g	Bq/g U-238 (calc)	Th-230	Ra-226	Pb-210	Th-232	Th-228
0-2	2.3 +/- 0.5	0.028 +/- 0.006	0.015 +/- 0.001	0.009 +/- 0.004	<0.2	0.018 +/- 0.001	0.022 +/- 0.001
2-5	1.9 +/- 0.1	0.024 +/- 0.001	0.021 +/- 0.001	0.021 +/- 0.005	<0.2	0.021 +/- 0.001	0.029 +/- 0.002
5-10	1.2 +/- 0.1	0.015 +/- 0.001	0.017 +/- 0.003	0.019 +/- 0.004	<0.2	0.017 +/- 0.003	0.016 +/- 0.003
10-15	1.4 +/- 0.1	0.017 +/- 0.001	0.016 +/- 0.003	0.016 +/- 0.003	<0.2	0.016 +/- 0.003	0.024 +/- 0.003
15-20	1.4 +/- 0.1	0.017 +/- 0.001	0.011 +/- 0.002	0.014 +/- 0.005	<0.2	0.018 +/- 0.003	0.018 +/- 0.003
20-25	1.0 +/- 0.1	0.012 +/- 0.001	0.012 +/- 0.002	0.007 +/- 0.003	<0.2	0.017 +/- 0.003	0.019 +/- 0.003

Several observations can be made

1) More than 90% of the uranium activity found in the Horseshoe Pond sediment, at all depths, is contained by the phase which dissolved due to the hydrogen peroxide treatment.

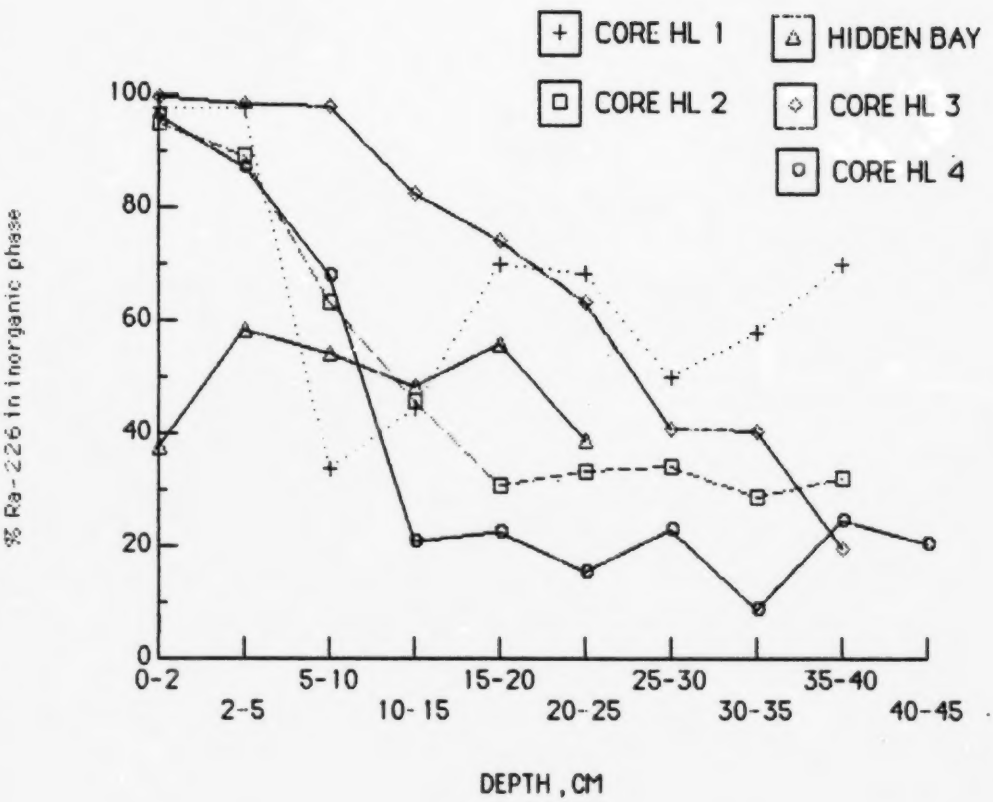
2) Over the first five centimeters of the Horseshoe Pond sediment cores, more than 80% of the Ra-226 is contained by the inorganic phase (see Figure 17), with the organic phase containing between 0.01 and 0.02 Bq/g. Deeper, the Ra-226 content of the organic phase remains the same but the Ra-226 content of the inorganic phase also decreases to between 0.01 and 0.02 Bq/g. At a depth of 10 centimeters or more the distribution of the radionuclides between the two phases resembles that of the Hidden Bay sediment core. The presence of excess Ra-226 in the inorganic portion of the sediment, coupled with the absence of Th-230, suggests that it is present as either adsorbed ions or as an independent inorganic species such as $RaSO_4$. There is also evidence of a second form of radium, associated with the organic phase.

3) More than 70% of the Pb-210 contained in the Horseshoe Pond surface sediment is attached to the inorganic phase. Since Pb-210 has a half-life of twenty-two (22) years and since it is supported by the Ra-226 activity present, it is not possible to conclude whether it arrived via in-growth from Ra-226 or whether it was adsorbed directly from solution as the ionic species Pb^{++} or some independent inorganic species, such as $PbSO_4$. The amount of Pb-210 present in the first 5 centimeters of cores HL-1, HL-2 and HL-3 is consistent with the amount that would be expected to grow in from Ra-226 over a five year time period.

4) The thorium isotopes, Th-232, Th-230 and Th-228, are predominantly present in the inorganic phase. This is consistent with the known

FIGURE 17

Distribution of Ra-226 in Sediment Cores
Between the Organic and Inorganic Phases



insolubility of thorium and suggests that it found its way into the sediment via terrestrial erosion and subsequent surface runoff.

5) Since it is apparent that most of the uranium is present in the organic phase, its U-234/U-238 ratio was determined for all sediment core sections. The results are included in Tables 16 and 18. Because of the low levels of uranium and the corresponding imprecision of the ratio measurement the results can not be interpreted. The U-234/U-238 ratio profile for the Horseshoe Pond whole sediment and for its organic phase is illustrated in Figures 18 and 19, respectively.

3.4 Total Organic Matter Content of Horseshoe Pond Sediments

The total organic matter contents of the Horseshoe Pond sediments determined in this report were carried out by the hydrogen peroxide oxidation procedure described in Section 1.5.2. Historical data available for the area were obtained by use of the loss on ignition (LOI) or dichromate oxidation (Allison 1965) procedures. The LOI procedure reports in units of % organic matter whereas the dichromate oxidation procedure repots in units of percent organic carbon. Allison (1965) has reported that the organic carbon contents of soils can be expressed as total organic matter contents by multiplying by the "Van Bemmelen factor" of 1.724. The use of this factor is based on the assumption that soil organic matter contains 58% carbon. Many studies have been reported on this factor with highly variable results indicating that it is only an approximation. Studies by Broadbent (1953) indicate that the factor for converting organic carbon to organic matter in surface soils is approximately 1.9. No such factor for organic matter in sediments has been reported. In order to allow comparisons between the three procedures as they are applied to lake sediments, a study was carried out, using Horseshoe Pond sediment core HL-3, to determine the relationship between the three methodologies. The results, tabulated in Table 20, show a good correlation between all three procedures. The factor for the conversion of organic carbon

FIGURE 18

Plot of U-234/U-238 Ratio in the Whole Sediment
of Horseshoe Pond as a Function of Depth

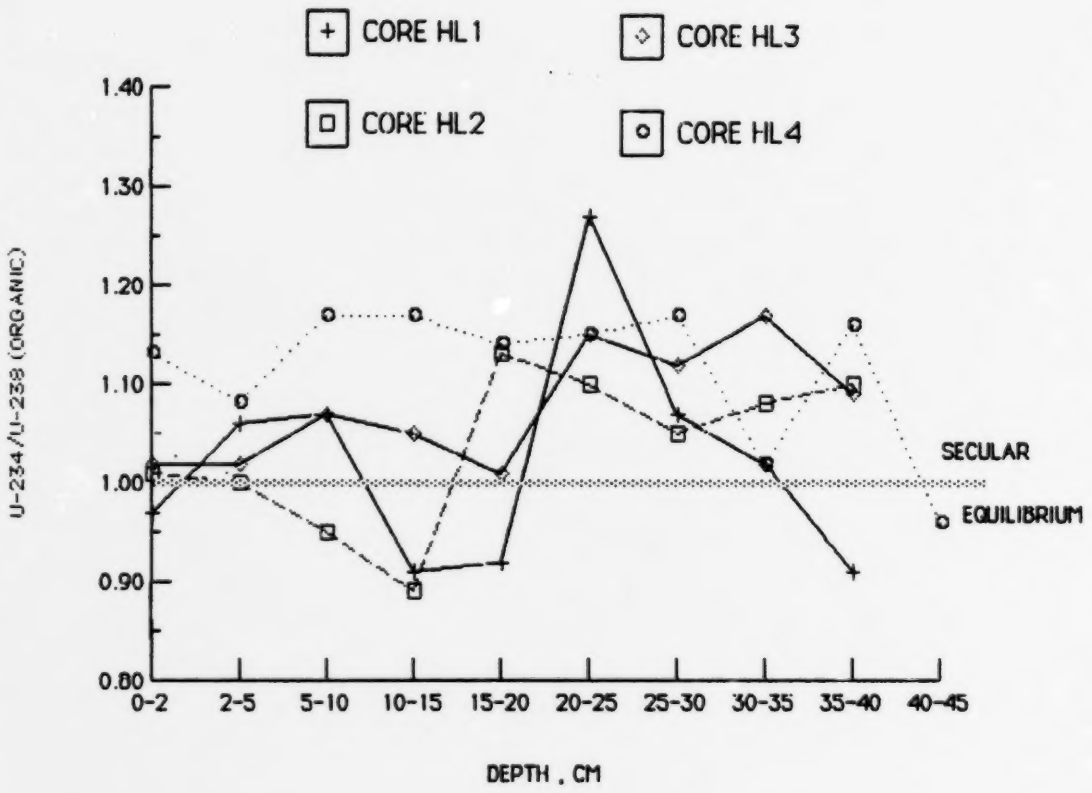


FIGURE 19

Plot of U-234/U-238 Ratio in the Organic Portion
of Horseshoe Pond Sediment as a Function of Depth

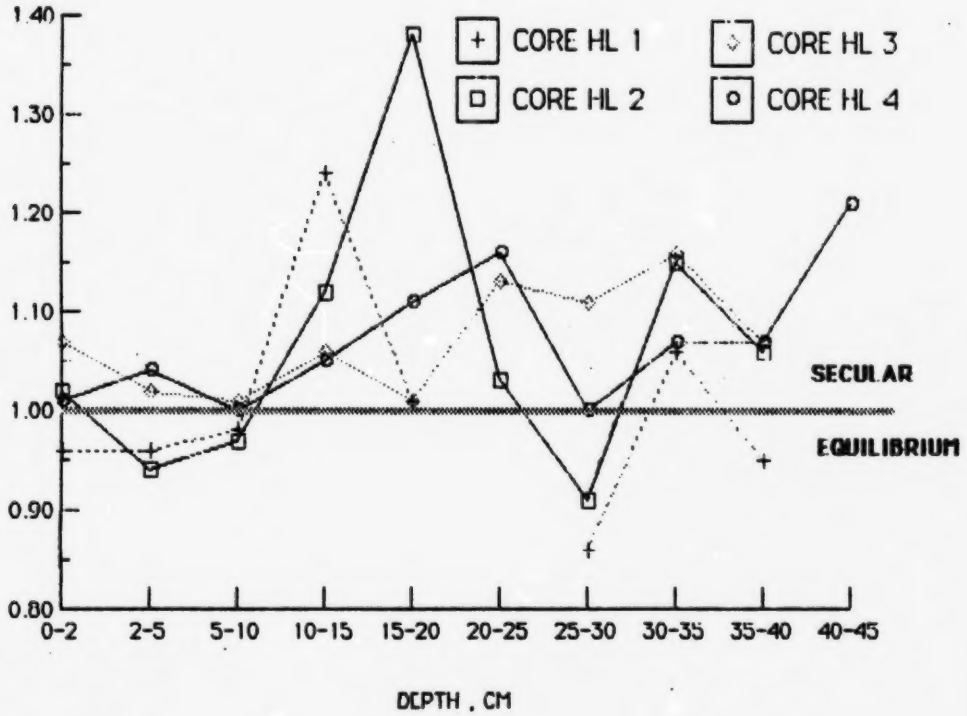


TABLE 20

Comparison of Methods for the Determination of Organic Contents of Lake Sediments

Sample Description	H_2O_2 Procedure, % organic matter	Dichromate Procedure, % organic carbon	LOI (1.5 h at 420°C), % organic matter
HL3-1	36.4	16.6	32.5
HL3-3	30.1	14.9	30.2
HL3-6	24.9	11.9	26.4
HL3-7	20.5	12	24.3
HL4-8	16.2	9.5	18.3
HL4-10	10.8	6.4	12.1

data (by dichromate oxidation) to organic matter data was calculated to be 1.9±0.2 using the H_2O_2 procedure and 2.0±0.2 using the LOI procedure. The total organic matter content as indicated by the hydrogen peroxide procedure is in close agreement with the organic matter content indicated by LOI.

In order to obtain some idea of the capacity of the organic matter for radionuclides the activities of uranium and Ra-226 were calculated per gram of organic matter (as given by the hydrogen peroxide oxidation procedure). The results for Horseshoe Pond sediment cores and Hidden Bay sediment core are shown in Tables 21 and 22. The maximum activity of uranium per gram of organic matter was found within the first 15 centimeters for the Horseshoe Pond cores and within the first 2 centimeters for Hidden Bay. The activity of Ra-226 contained in every gram of organic matter was constantly low throughout all cores taken. The concentration of uranium contained by the organic matter was highest at the surface, reaching 38 Bq/g, and decreased rapidly with depth. If an equilibrium exists between the uranium contained by the lake water and the uranium contained by the organic matter phase, these figures may reflect the relative concentrations of uranium in the lake water at the time of sediment deposition. In 1972, Cameron and Ballantyne (1977) surveyed the lakes in the Rabbit Lake area and found a strong correlation between the uranium contained in the surface sediment and the uranium contents of the lake water.

For comparison purposes, the uranium activity per gram of organic matter for the historical data in Tables 4, 7 and 10 were calculated and normalized to the hydrogen peroxide procedure. The results are shown in Table 23.

3.5 Estimated Impact of Mining Operation on Horseshoe Pond and Its Sediment

Under the terms of this study four sediment cores were taken from Horseshoe Pond. With the limited amount of resulting data, it is difficult to

TABLE 21 Activity level per gm organic matter and Activity ratios in organic portion of Horseshoe Pond sediment (calculated from TABLE 16)

	Bq/gram			Activity Ratio		
DEPTH , CM	U-238 organic	Ra-226 organic	Pb-210 Organic	U-234 U-238	U-238 Ra-226	Ra-226 Th-230
CORE HL1						
0-2	31.7	0.1	0.5	0.97	441.3	0.9
2-5	24.2	0.1	<0.2	1.06	416.7	0.8
5-10	12.1	0.9	<0.2	1.07	13.4	-18.5
10-15	4.4	0.5	<0.2	0.91	8.4	2.5
15-20	1.4	0.3	<0.2	0.92	4.7	-0.7
20-25	0.2	0.3	<0.2	1.27	0.7	2.3
25-30	0.6	0.2	<0.2	1.07	3.5	5.0
30-35	0.6	0.2	<0.2	1.02	3.4	4.0
35-40	0.7	0.2	<0.2	0.91	4.1	0.7
CORE HL2						
0-2	37.4	0.1	0.5	1.01	544.4	0.6
2-5	20.0	0.1	0.5	1.00	292.3	-7.5
5-10	2.8	0.1	<0.2	0.95	32.2	3.7
10-15	0.7	0.2	<0.2	0.89	4.1	8.3
15-20	0.7	0.2	<0.2	1.13	3.2	5.8
20-25	0.7	0.2	<0.2	1.10	3.3	1.6
25-30	0.7	0.2	<0.2	1.05	3.0	9.7
30-35	0.8	0.3	<0.2	1.08	2.7	-5.8
35-40	1.6	0.3	<0.2	1.10	5.3	-6.0
CORE HL3						
0-2	27.0	0.0	< 0.2	1.02	1968.6	0.1
2-5	20.8	0.0	0.4	1.02	1579.7	0.2
5-10	15.8	0.0	<0.2	1.07	1587.9	0.5
10-15	3.9	0.0	<0.2	1.05	112.4	1.5
15-20	2.1	0.0	<0.2	1.01	59.0	3.0
20-25	0.8	0.1	<0.2	1.15	13.9	1.2
25-30	0.6	0.1	<0.2	1.12	5.3	1.8
30-35	0.6	0.2	<0.2	1.17	4.1	-3.4
35-40	0.8	0.2	<0.2	1.09	3.3	-9.0
CORE HL4						
0-2	28.3	0.0	<0.2	1.13	816.1	0.5
2-5	18.5	0.1	<0.2	1.08	350.1	4.7
5-10	18.5	0.1	<0.2	1.17	189.8	1.6
10-15	4.6	0.1	<0.2	1.17	30.7	17.0
15-20	1.1	0.2	<0.2	1.14	5.1	4.1
20-25	1.3	0.2	<0.2	1.15	5.8	-39.0
25-30	1.6	0.2	<0.2	1.17	6.5	6.2
30-35	1.7	0.3	<0.2	1.02	5.4	-3.5
35-40	1.6	0.2	<0.2	1.16	6.7	-11.3
40-45	2.0	0.4	<0.2	0.96	5.0	-7.2

TABLE 22 ACTIVITY LEVEL PER GRAM ORGANIC MATTER AND ACTIVITY RATIOS IN ORGANIC PORTION OF HIDDEN BAY SEDIMENT (calculated from TABLE 18)

	Bq/gram		Activity ratio		
DEPTH,CM	U-238 organic	Ra-226 organic	U-234 / U-238	U-238 / Ra-226	Ra-226 / Th-230
0-2	11.0	0.3	0.95	36.0	2.5
2-5	1.4	0.2	1.03	6.5	15
5-10	1.1	0.3	1.18	3.7	NA
10-15	0.9	0.4	1.02	2.5	-3.4
15-20	0.9	0.4	1.09	2.1	NA
20-25	1.0	0.5	1.08	2.1	2.2

TABLE 23

Uranium Activity Levels per Gram of Sediment Organic Matter
Data is Historical Data Normalized to Hydrogen Peroxide Procedure

	Depth, cm	U-238, Bq/g Carbon Matter
1974 (Taken from Table 4)		
Rabbit Lake - North Shore	Surface	14
- South Shore	Surface	17
Upper Link Lake	Surface	6
Lower Link Lake	Surface	5
Pow Bay	Surface	1.2
1980 (Taken from Table 7)		
Upper Link Lake	0-2	448
	2-4	128
	4-6	20
	6-8	18
	8-10	16
	10-12	11
	12-14	9
	14-16	4
	16-18	4
Horseshoe	0-4	7
	4-6	1
	6-8	0.8
	8-10	1
	10-12	0.6
Hidden Bay	0-2	20
	2-5	14
	5-10	7
1982 (Taken from Table 10)		
Upper Link Lake	0-2	600
	2-3	1582
	3-4	1688
	4-5	1952
	5-6	868
	6-7	206
	7-8	134
	8-9	54
	9-10	1

make quantitative conclusions. The following calculations are based upon available data and their significance should be considered from that point of view.

Over the past five years, the estimated average flow rate from the Eldor Mines Limited tailings pond into Horseshoe Pond has been given as 3,000 liters per minute (6,900 liters per minute in 1985) (Filion 1986). The estimated average uranium concentration was 580 µg/L (ppb) and the radium-226 activity was 0.3 Bq/L (Filion 1986). These figures translate into mass flows into Horseshoe Pond of 4.6×10^{12} µg uranium and 2.4×10^{9} Bq radium-226 for the five year period.

The estimated area of Horseshoe Pond is 32,000 square meters. Since the sediment analysis data, contained in this report, suggests that, over the past 5 years, the first 5 centimeters of lake sediment have accumulated uranium and radium-226, it may be concluded that 1600 cubic meters of sediment has adsorbed radioactivity. The density of the dried sediment (first five centimeters) was found to be approximately 0.5 gm/cm^3. Therefore, the first five centimeters of lake sediments weights 8×10^{8} grams. If all of this sediment adsorbed all of the available uranium and radium-226, over the past 5 years, it would contain 5,800 µg uranium per gram and 3 Bq radium-226 per gram. The data in Table 14 show that, in fact, the Horseshoe Pond sediment contains only 500 ± 200 µg uranium and 0.5±0.2 Bq radium-226 per gram. This implies that 5-12% of the uranium and 10-20% of the radium-228, available from the effluent treatment system, has been accumulated by Horseshoe Pond bottom sediments.

Another way to estimate the influence of Horseshoe Pond sediment on uranium removal is to compare the uranium concentration in the surface water at the lake inlet and at the lake outlet with the concentrations of other cations in the surface water at the same locations. Table 11 shows that sulfate, chloride, calcium, magnesium, manganese, sodium ions and TDS concentrations at the outlet were each 68 ± 2% of their concentrations at the inlet. This decrease may be attributed to dilution caused by surface water

runoff to Horseshoe Pond. The fact that uranium decreased to 58% of its inlet concentration (86 ppb to 50 ppb) suggests that approximately 10% of the uranium, or 8 ppb, has disappeared, perhaps by adsorption onto the lake sediment. In other words, both methods of estimation suggest that approximately 10% of the available uranium contained in Horseshoe Pond water has been accumulated by its sediment.

IV. SUMMARY

Four sediment cores were taken from Horseshoe Pond and one from Hidden Bay. The interstitial water was removed from the Horseshoe Pond sediments and analysed along with the dried sediments. The results were interpreted with the objective of elucidating how radionuclides find their way onto lake sediment and whether adsorption/desorption processes are ongoing. Considering the limited amount of data obtained, several trends were noted and possible mechanisms suggested. They can be summarized as follows:

- From the interstitial water analysis, it appears unlikely that the upward movement of ground water through the Horseshoe Pond sediment is taking place. The net downward movement of lake water into the sediment appears more likely but simple hydrological measurements are needed to confirm this hypothesis.

- In each sediment core, the highest activities were found at shallow depths (0 to 15 cm) and belonged to U-238, U-234, Ra-226 and Pb-210.

- The sediments had an organic matter content that varied between 5 and 40 percent.

- For the first 5 centimeters, the Ra-226 activity considerably exceeded the Th-230 activity. Detailed analyses of the sediment showed that 80% of the Ra-226 and Th-230 were attached to the inorganic phase. At the shallow depths, secular equilibrium between the two did not exist in the inorganic phase. This is taken to be an indication that the majority of the Ra-226 arrived either by adsorption, as an ionic species from solution, or by precipitation as an independent solid, such as barium sulfate. At greater depths, equilibrium between Ra-226 and Th-230 was approached in the inorganic phase, suggesting that they found their way to the sediment by solid deposition of solids eroded from the earth's surface.

- The highest activity in the sediments belonged to uranium. For the first 10 to 20 centimeters, the uranium activity exceeded the Th-230 activity by more than 30 times. Detailed analysis of the organic and inorganic portions of the sediment suggest that 90% of the uranium was contained by the organic matter. There appeared to be no direct relationship between the organic matter content of the sediment and its uranium content. Comparison of the activity per gram of organic matter, found in this study, with the limited amount of historical data available for Horseshoe Pond suggests that the composition of first 5 to 10 centimeters of pond sediment reflect the influence of the recent mining activity and the resulting increase in concentration of uranium in the lake (pond) water. The sediment core taken from Hidden Bay at the outflow from Horseshoe Pond had uranium and Ra-226 activities in its sediment surface ten times lower than in Horseshoe Pond.

- More than 70% of the Pb-210 contained in the Horseshoe Pond surface sediment appears to be attached to the inorganic phase. It is entirely supported by Ra-226 activity. As a result, it can not be concluded whether it arrived via in-growth from Ra-226 or whether it was adsorbed or precipitated directly from solution. The activity of Pb-210 present in Horseshoe Pond sediment is consistent with the activity that would be expected to grow in from Ra-226 over a 5-year time period.

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APPENDIX

APPENDIX -- Data from the analysis of interstitial water removed from sediment cores taken at Horseshoe Pond

INTERSTITIAL SAMPLE NO.	DEPTH.CM.	pH	mg/L SO4	Cl	Ba	Ca	Fe	K	Mg	Mn	Na	anions / cations
HL1-1	0-2	6.14	3735	77	0.06	220	1.00	2.7	787	2.5	52	1.0
-2	2-5	6.31	4320	88	0.05	240	0.91	2.4	850	2.1	57	1.1
-3	5-10	6.07	4356	102	0.06	280	2.00	2.7	798	2.9	65	1.1
-4	10-15	7.08	4626	110	0.07	310	0.58	2.1	903	2.9	67	1.1
-5	15-20	6.81	4662	113	0.05	320	0.20	2.9	924	2.9	62	1.0
-6	20-25	5.85	4554	118	0.10	330	2.90	2.5	808	3.7	73	1.1
-7	25-30	7.40	4518	105	0.07	310	0.40	4.3	892	2.0	63	1.0
-8	30-35	6.60	2808	97	0.06	230	0.19	4.8	525	2.3	54	1.1
-9	35-40	IS	IS	IS	IS	IS	IS	IS	IS	IS	IS	IS
HL2-1	0-2	6.53	3258	58	0.06	200	0.40	2.3	735	2.0	38	1.0
-2	2-5	6.44	3636	58	0.09	220	0.81	2.4	777	1.9	40	1.0
-3	5-10	6.94	3780	69	0.05	220	0.15	3.9	756	1.3	43	1.1
-4	10-15	6.87	1881	56	0.05	140	0.20	5.0	336	1.1	33	1.1
-5	15-20	7.08	891	138	0.05	87	0.22	5.4	137	0.7	20	1.3
-6	20-25	7.30	486	77	0.07	73	0.27	6.8	79	0.3	14	1.1
-7	25-30	6.82	239	24	0.05	33	0.27	5.4	27	0.2	7.2	1.3
-8	30-35	6.90	130	16	0.07	39	0.28	7.1	12	0.1	3.6	1.0
-9	35-40	IS	IS	IS	IS	IS	IS	IS	IS	IS	IS	IS
HL3-1	0-2	6.40	2952	56	0.05	200	0.64	1.0	703	2.1	40	0.9
-2	2-5	6.00	4014	75	0.04	240	1.50	1.0	882	2.0	47	1.0
-3	5-10	6.63	5265	97	0.05	290	0.21	1.3	1050	2.5	58	1.1
-4	10-15	6.96	5859	129	0.05	350	0.46	1.7	1260	3.3	79	1.0
-5	15-20	6.26	7056	162	0.06	410	0.31	1.9	1470	3.9	93	1.0
-6	20-25	7.16	4158	143	0.05	340	0.12	2.9	662	6.0	77	1.2
-7	25-30	7.34	3033	135	0.06	320	0.23	4.0	430	7.1	71	1.2
-8	30-35	5.16	2430	124	0.06	280	2.20	5.2	304	7.6	57	1.3
-9	35-40	6.22	1764	110	0.05	220	1.30	4.5	189	6.6	47	1.4
HL4-1	0-2	6.37	3420	67	0.04	200	0.21	1.4	714	2.0	36	1.0
-2	2-5	6.80	4320	80	0.04	250	0.12	1.8	892	2.0	47	1.0
-3	5-10	6.93	4734	94	0.05	300	0.10	2.3	987	2.9	62	1.0
-4	10-15	6.82	4914	110	0.04	340	1.00	1.7	1039	3.6	69	1.0
-5	15-20	6.89	3105	91	0.04	220	0.12	2.9	651	2.4	59	1.0
-6	20-25	7.40	1827	83	0.04	170	0.34	3.4	325	2.6	49	1.1
-7	25-30	IS	IS	IS	IS	IS	IS	IS	IS	IS	IS	IS
-8	30-35	6.68	1656	102	0.07	200	0.65	7.1	263	4.6	47	1.1
-9	35-40	IS	IS	IS	IS	IS	IS	IS	IS	IS	IS	IS
-10	40-45	IS	IS	IS	IS	IS	IS	IS	IS	IS	IS	IS